Part IV:

MEASURE ANALYSIS and LIFE-CYCLE COST

2005 California Building Energy Efficiency Standards

CALIFORNIA
ENERGY
COMMISSION

Contract Number
400-00-061

P400-02-014
August 13, 2002

Gray Davis, Governor

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San Francisco
Contract Number 400-00-061
August 13, 2002

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Introduction

This report contains the results of initiatives to upgrade and improve the 2001 California energy efficiency standards for residential and nonresidential buildings. The revisions will be adopted in 2003 for implementation in 2005.

Potential measure analysis initiatives and proposed standards changes were submitted and discussed at staff workshops on October 22, November 15, and November 16, 2001. The California Energy Commission (CEC) identified priority measures and funded analysis initiatives on a subset of these measures. SCE funded VAV Staged Control. Other parties have also funded further analysis initiatives; however these analyses are not included in this document.

This document contains Part IV of the report, which includes the measures analyzed under contract to the CEC that will be discussed in a staff workshop on August 27, 2002. Part I contained the measures discussed at the April 23, 2002 workshop, Part II included the measures covered during a workshop on May 30, 2002, and the measures discussed at the July 18, 2002 workshop appeared in Part III.

Summary of Measures

The following measures and modifications are addressed in this document:

Electrically-Commutated Motors in Series Terminal Units. This proposal adds to §144(b), Power Consumption of Fans, the new requirement that fan motors of 1 hp or smaller used in series terminal units be electronically-commutated motors (ECM). There is currently no specific requirement for this fan application. These ECM motors are more efficient than AC induction motors in small sizes and at partial loads.

Size Threshold for Variable Speed Drives. §144(b)2 currently requires that variable air volume (VAV) fans over 25 hp have either a variable speed drive or other specific means of reducing fan power at partial flow. This change reduces the fan size threshold from “larger than 25 hp” to “10 hp or larger.”

Lay-In Insulation in Nonresidential Buildings. This report shows that insulating the roof deck and the sidewalls of the plenum below the roof deck instead of laying insulation directly on a t-bar ceiling is clearly cost-effective when amortized over the course of 30 years when the plenum heights are less than 12 feet tall. It is proposed, therefore, to restrict the use of insulation on ceilings, except for cases where the plenum space between the ceiling and roof exceeds 12 feet in height.

Acknowledgements

This project was completed by Eley Associates and its subcontractors. Charles Eley is the project manager for the contractor team. Kimberly Got assisted with editing and report production.

Electrically-Commutated Motors in Series Terminal Units and *Size Threshold for Variable Speed Drives.* This research for these measures was conducted by Lanny Ross of Newport Design Consultants. The material was reviewed by Mark Hydeman and Steve Taylor of Taylor Engineering. Charles Eley and Erik Kolderup provided guidance, technical editing, and cost and simulation data. Additional information was provided by Skip McGowan of Danfoss Graham, Steve Weston of DMG Corporation, Chuck Hayden of the Trane Company and Isaac Scott of York International Corporation.

Lay-In Insulation in Nonresidential Buildings. This research was funded by the California Energy Commission under Public Interest Energy Research (PIER) contract No. 400-99-013 *Integrated Energy Systems - Productivity and Buildings Science* energy research program managed by the New Buildings Institute. Cathy Higgins is the Program Director of this project for the New Buildings Institute. The PIER program is funded by California ratepayers through California's Public Benefit Charges and is administered by the California Energy Commission (CEC). Donald J. Aumann is the CEC project manager.

Distilling this research into a code proposal for the 2005 revisions to the Title 24 standards is funded by the California Energy Commission through a contract with Eley Associates.

The building energy simulation model was developed and runs were processed by Peter Jacobs of Architectural Energy Corporation under a contract with the Pacific Gas & Electric Company in support of energy efficiency upgrades to the 2005 California Building Efficiency Standards.

Mark Modera of Modera Consulting Engineers helped to develop models of duct system performance that would be compatible with the calculation procedures in ASHRAE Standard 152P. The Pacific Gas & Electric Company's Codes and Standards Enhancement (CASE) program also funded Mr. Modera's work.

Special thanks also goes to Mr. Bill Beakes and Bill Franz of Armstrong World Industries, Rick Diamond of Lawrence Berkeley National Laboratory, and Jim Cummings of the Florida Solar Energy Center.

Electronically-Commutated Motors in Series Terminal Units

Overview

Description

In a typical nonresidential building, the fans run continuously to provide ventilation. In California, fan energy is as large, or larger, than the heating and cooling energy (based upon modeling and metering). Fan-powered mixing boxes are used in many nonresidential buildings. They incorporate a small motor that helps circulate the air. The motor in series fan boxes is typically only 40-50% efficient (and can be as low as 15-20% efficient when not operating at peak load). Such motors have primitive speed control that is also inefficient. Because of the number of fan-powered boxes in some nonresidential buildings, the total fan power in these little motors can represent as much as one-quarter of the total installed fan power. However, because these small, inefficient motors run continuously while the central fan modulates on a variable frequency drive (VFD), they consume half of the energy used for fans in buildings with series fan-powered mixing boxes.

With a series fan-powered box in an air terminal unit, primary air from the HVAC unit, cooled to the supply air temperature setting, enters the box in a quantity determined by the space load. The primary air is mixed with secondary air drawn from the space or the plenum. The fan delivers the mixed air through supply air diffusers. The fan operates continuously when the space is occupied. By contrast, in a parallel fan-powered box, the fan operates intermittently to circulate return air from the ceiling plenum to the space, operating only when the primary airflow drops to its minimum setpoint.

This measure would require that motors located in series fan-powered boxes be electronically commutated. Electronically-commutated motors provide significant energy savings in such applications. The measure would not apply to parallel fan-powered boxes.

A series fan-powered box is often used in a variable air volume system to maintain relatively constant airflow at the zone level. When sufficient heat load is not present in the zone, the primary air volume will reduce to a point where the air circulation rate may be insufficient to satisfy occupant comfort due to a perception of stuffiness from lack of air movement, poor diffuser performance at low flows, or incomplete air mixing in the space. The use of a fan-powered box enables the zone airflow rate to remain satisfactory while allowing the primary airflow to drop.

Series fan-powered boxes are available in different physical sizes for applications between 400 cfm and 2,000 cfm. The fan motors are typically either ¼, ½, ¾, or 1 hp. In larger units, multiple fans and motors may be used.

Small induction motors are often utilized for the fans in fan-powered boxes. An alternating current (AC) induction motor is extremely inefficient in sizes under 1 hp and at light loads. A direct current (DC) motor is efficient at part load and in small sizes. However, until recently DC motors carried the burden of a commutator and brushes to provide alternating current to the armature coils and create the changing magnetic fields that rotate the armature.

The development of electronics that reverses the polarity of a DC power supply frees DC motors from the commutator, the associated carbon brushes, and the attendant high maintenance. Another advance in motor technology is the use of permanent magnets in the armature instead of coils to produce a rotating field. The rotating magnetic field is now produced by the stator (stationary coils placed within the shell of the motor) with the switching of the power current done electronically. There are several names for this type of motor including brushless DC motors, but the most popular seems to be “electronically-commutated motor” and ECM will be utilized as an abbreviation in this document.

Furthermore, a DC drive motor is variable speed with a very wide range of permissible speeds, meaning that the airflow (cfm) of the fan-powered box may be adjusted electronically with the drive controller. The drive controller circuitry is located within the motor shell and is an integral part of the motor/controller assembly. A standard 4 to 20 milliamp or 0 to 10 volt signal resets the fan speed. An ECM operates at relatively constant speed regardless of load. A programmed integrated circuit in the motor contains fan curve data, and the motor electronics sense rpm and torque. With that information, a properly programmed motor can maintain airflow within 5% of the set point.

At light loads the difference in energy consumption between an ECM and the base case induction motor is significant. At full load the difference is much less, but it is unusual for an HVAC motor to be fully loaded because motors are manufactured in discrete capacity steps and a designer normally chooses a motor above the estimated power draw of the load.

The energy savings are calculated by comparing the ECM motor to the base case induction motor. The magnitude of the savings varies depending on how heavily the induction motor is loaded (fraction of rated running load amperes, or RLA, of the induction motor). Theoretically, a fully loaded induction motor and a fully loaded ECM would consume the same amount of power if the AC power factor were unity.

Benefits

This measure reduces energy use in nonresidential buildings by requiring ECM motors in series fan-powered mixing boxes. The measure would have no impact on indoor air quality or thermal comfort. Electric peak demand also would be reduced, since series fan-powered boxes typically operate under utility peak load conditions. Reduced energy use also results in cleaner outside air because of fewer emissions at power plants.

Environmental Impact

There are no negative environmental impacts associated with ECM motors. Positive impacts are related to reduced energy use and reduced demand for electricity.

Type of Change

The proposed change would be implemented as a prescriptive requirement. It would be the basis of the standard design in performance calculations, but would not be mandatory. The proposed change expands the scope of the standards to include series fan-powered box motors.

Availability and Cost

Electronically-commutated motors are an option offered by all the major mixing box manufacturers. GE is the most well know manufacturer of the motors, FASCO has an equivalent motor, and Emerson is releasing what they are calling an ECM.

There are various incremental, additional cost figures that are mostly quoted around $250. This cost is over and above the cost of an induction motor and is primarily for the added electronics to switch the polarity of the DC power. When this requirement was adopted into the Seattle Energy Code, the estimate of cost was $150-$230 per mixing box. At one box per 1,000-2,000 ft^2, the cost is roughly $0.15/ ft^2 of building space.

Electrical distribution system costs might be higher for ECMs in some cases. ECM fan-powered boxes are typically offered with fewer motor size options. Even though, for example, a ½ hp ECM would usually draw less power than a ¼ hp induction motor in a fan-powered box application, the electricity supply still needs to be sized for the motor's peak RLA. The overall impact is not clear. There is unlikely to be much impact on conductor size because wires are typically larger than necessary for such small loads already. The impact on other distribution system components will vary from case to case depending on whether the ECMs would require a jump in component size. The average extra cost is expected to be fairly low and has not been included in this analysis.

An ECM may incur extra replacement costs relative to an induction motor because the ECM has a proprietary program loaded by the fan-powered box manufacturer. Replacement motors will most likely have to be purchased from the original equipment manufacturer.

ECM motors are presently being used in variable-speed forced air furnaces and air conditioners. They also are in prototype development to power domestic refrigerators. The motors are also used in variable speed small industrial refrigeration compressors. The fan-powered box design does not change. There are no modifications necessary to the box with the possible exception of mounting brackets for the motor.

Useful Life, Persistence and Maintenance

The mean life-to-failure is reported to be 90,000 hours, which is equal to about 21 years based on typical operation of 4,240 hours per year (equivalent to the nonresidential operating schedule in the ACM Manual). There are no maintainable components contained in the motor. The energy savings will persist for the entire life of the motor.

Performance Verification

An ECM series fan-powered box will deliver relatively constant airflow regardless of the discharge pressure of the fan. Therefore, the design airflow can be set at the factory.

Methodology and Results

Since the measure is proposed to be a prescriptive requirement, it is necessary to show that it is cost effective using the life-cycle cost methodology established for this project. The procedure is as follows:

- Estimate the electricity savings from use of an ECM motor in a series terminal unit.
- Calculate the present value of these savings by multiplying the kWh per year times $1.37, which accounts for the present value of energy costs over a lifetime of 15 years.
- Show that the cost premium for the ECM motor is less than the present value of the energy savings.

Fan power estimates come from two fan-powered box manufacturers: Nailor[1] and Titus[2]. Those data compare performance of ECMs and permanent split capacitor (PSC) induction motors. For energy calculations, the hours of operation are assumed to be 4,240 hours per year, equal to the nonresidential occupancy schedule (Table 2-4) in the 2001 Nonresidential ACM Approval Manual.

Technical literature from Carrier Corporation, Nailer Industries Inc. and General Electric Control Systems is reviewed as part of this study. A conversation with both GE and Nailer technical staff provides additional information with respect to mean life-to-failure and availability issues.

Electricity Savings

Fan power is illustrated in Figure 1 for ECMs and the baseline induction motors over a range of airflows typical for fan-powered boxes. In all cases, the AC induction motors require more power than the corresponding ECM. Figure 3 shows the power savings, which range from a low of about 110 W up to 390 W. There is a significant amount of variation in savings because in some cases more than one size of induction motor might be selected to provide the same airflow as a single ECM. For example, savings are low when airflow is at the high end of the ½ hp induction motor range (about 1,400 cfm). Savings increase at the point when a ¾ hp or 1 hp induction motor is required (because of the poor part load efficiency of the induction motor).

The savings results are summarized in Table 1 and presented as ranges. The estimated energy savings range from 466 to 1,654 kWh per year depending on the airflow. The corresponding life cycle energy savings are $639 to $2,265.

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[1] Nailer Industries Bulletin ECM-1.98.

[2] Titus document number: MG-ECM-01.

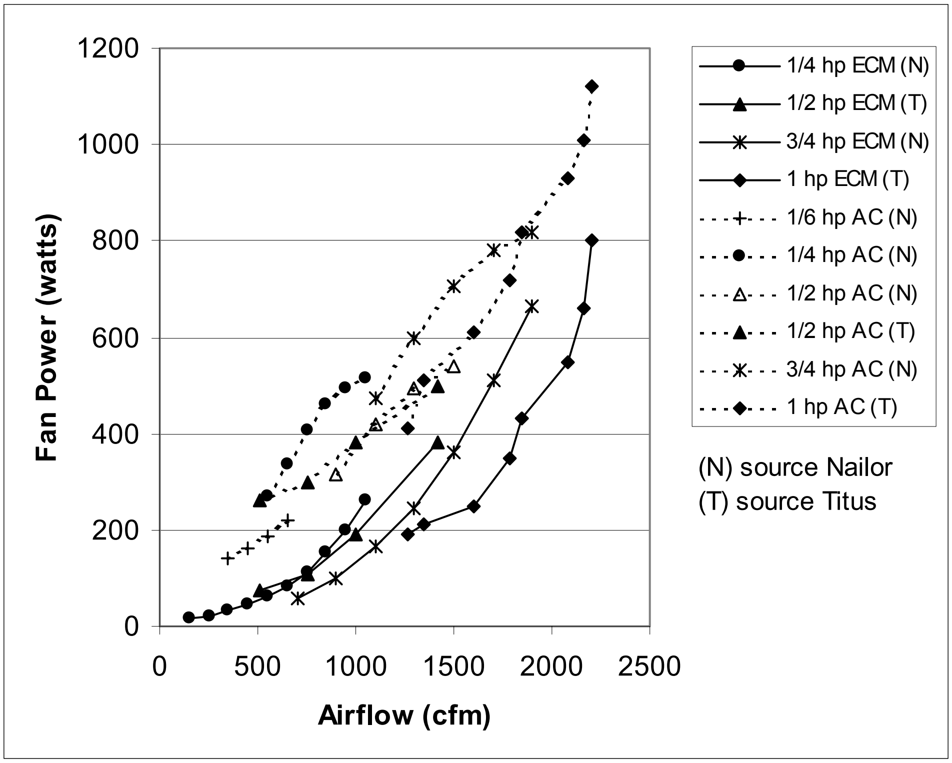

Figure 1 – Fan Power vs. Airflow for ECMs and Induction (AC) Motors Based on Manufacturers' Data

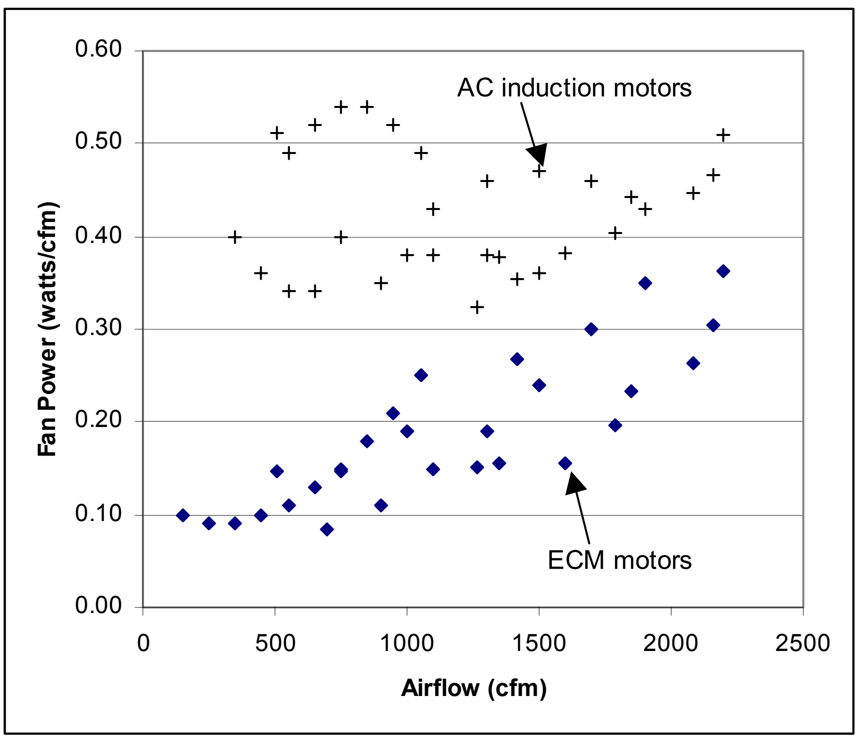

Figure 2 – Fan Power vs. Airflow for ECMs and Induction (AC) Motors Based on Data from Figure 1

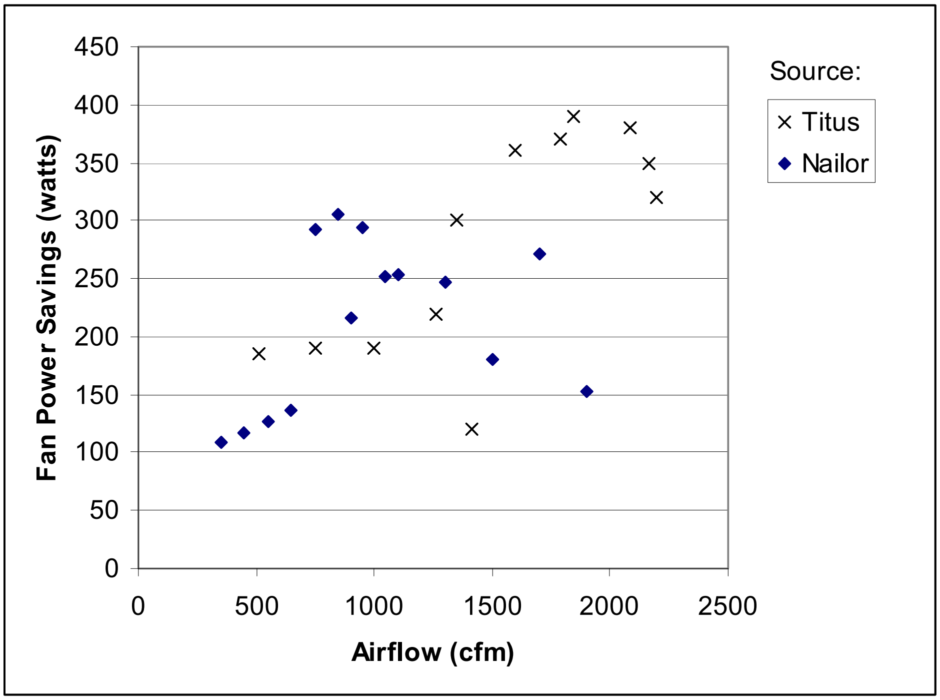

Figure 3 – Electric Demand Savings for ECMs vs Induction Fan Motors
Each point represents the difference in power between an ECM motor and an induction motor of comparable size. Titus data includes ½ hp and 1 hp motors. Nailor data includes ¼ and ¾ hp ECMs and 1/6, ¼, ½, and ¾ hp induction motors.

Table 1 – ECM Power, Energy and Life-Cycle Energy Cost Savings

Airflow (cfm)	**Savings (watts)**		**Savings (kWh/yr)**		**Savings ($ present value)**	
	Low	High	Low	High	Low	High
500	110	185	466	784	$639	$1,075
1000	190	310	806	1,314	$1,104	$1,801
1500	120	320	509	1,357	$697	$1,859
2000	150	390	636	1,654	$871	$2,265

The savings presented in Table 1 do not include the additional benefit of the ability to either globally or individually reduce the speed of the motors during periods of light occupancy. In addition, no credit was taken for the box not requiring field test and balance. Rebalance, if necessary, is done from a curve of cfm versus imparted voltage on one of the motor's inputs and adjusting the voltage to match the new cfm.

Measure Cost

Manufacturers surveyed for this study report incremental costs of $155 to $250 per motor for ECMs compared to induction motors with silicon controlled rectifier (SCR) speed control. The size of the motor does not affect the cost of the electronics. Assuming a 30% distributor and contractor markup, the incremental installed cost increases to a range of $200 to $325.

Cost Effectiveness

The minimum life-cycle energy savings as listed in Table 1 is $639, and the upper end of the incremental cost range is $325. Therefore, the measure is cost effective based on even relatively conservative assumptions.

Recommendations

The following changes are recommended so that electronically-commutated motors are required in series fan-powered boxes of 1 hp or less that are used in VAV systems. To allow for future technologies with comparable efficiency, an alternative allows other motor types that have a minimum full load efficiency of 70%. Currently, very few AC motors in this size range achieve 70% efficiency. On the other hand, the typical full load efficiency for an ECM is 75-80%.

Proposed Standards Language

The following definition should be added to §101(b) of the standards:

> **ELECTRONICALLY-COMMUTATED MOTOR** is a brushless DC motor with a permanent magnet rotor that is surrounded by stationary motor windings, and an electronic controller that varies rotor speed and direction by sequentially supplying DC current to the windings.

The following change is recommended to §144(c) of the standards.

(c) **Power Consumption of Fans.** Each fan system used for comfort space conditioning with a total fan power index over 25 horsepower shall meet the requirements of Item 1 or 2 below, as applicable. Total fan system power demand equals the sum of the power demand of all fans in the system that are required to operate at design conditions in order to supply air from the heating or cooling source to the conditioned space, and to return it back to the source or to exhaust it to the outdoors; however, total fan system power demand need not include the additional power demand caused solely by air treatment or filtering systems with final pressure drops more than one-inch water column (only the energy accounted for by the amount of pressure drop that is over one inch may be excluded), or fan system power caused solely by process loads.

1. **Constant volume fan systems.** The total fan power index of each fan system at design conditions shall not exceed 0.8 watts per cfm of supply air.

2. **Variable air volume (VAV) systems.**

   A. The total fan power index of each fan system at design conditions shall not exceed 1.25 watts per cfm of supply air; and

   B. Individual VAV fans with motors over 25 horsepower shall meet one of the following:

      i. The fan motor shall be driven by a mechanical or electrical variable speed drive.

      ii. The fan shall be a vane-axial fan with variable pitch blades.

      iii. For prescriptive compliance, the fan motor shall include controls that limit the fan motor demand to no more than 30% of the total design wattage at 50% of design air volume when static pressure set point equals 1/3 of the total design static pressure, based on certified manufacturer's test data.

   C. Fan motors of 1 horsepower or less in series terminal units shall be electronically-commutated motors or shall have a minimum motor efficiency of 70% when rated in accordance with NEMA Standard MG 1-1998 Rev. 2 at full load rating conditions.

3. **Air-treatment or filtering systems.** For systems with air-treatment or filtering systems, calculate the adjusted fan power index using the following equation:

Adjusted fan power index = Fan power index x Fan adjustment

$$\text{Fan adjustment} = 1 - \left(\frac{SP_a}{SP_f}\right)$$

WHERE:

SP_a = Air pressure drop across the air-treatment or filtering system.

SP_f = Total pressure drop across the fan.

Size Threshold for Variable Speed Drives

Overview

Description

Variable air volume HVAC systems are more efficient when air volume is controlled by changing the speed of the fan. Other methods of air volume control are inlet vanes on centrifugal fans or discharge dampers. The current Title 24 standards require mechanical or electrical variable speed drives (VSD) for fan motors larger than 25 hp. The most common method of controlling fan motor speed is with an electronic variable frequency drive, although motor speed can also be controlled by mechanical drives with mechanical sheaves. Electronic variable frequency motor drives are now highly reliable and inexpensive in motor sizes down to 5 hp. This proposed standards change would reduce the size threshold for which VSD control of variable air volume fans would be required. In the context of this study, the generic term “variable speed drive” is used, but economic results are based on variable frequency drive technology.

Benefits

The major benefit of requiring VSD for fan motors below 25 hp is to reduce fan energy. Reduced fan energy will reduce operating cost for building owners, reduce air pollution (less fossil fuel burned to produce electricity), and will reduce the need to construct new power plants. While most VSD savings typically occur during non-peak hours, typical oversizing of fans results in savings during on-peak periods as well.

When installed with DDC control systems, VSDs can achieve additional savings by dynamically resetting the static pressure sensor set point on the zone VAV box requiring the most pressure; i.e., the set point is reset lower until one zone VAV box damper is nearly wide open. This reset strategy (Fan Pressure Optimization) is required as part of ASHRAE Standard 90.1-1999.

Environmental Impact

Installation of VSDs will lower energy usage. This will result in lowering emissions from power plants. VSDs reduce the speed of the rotating equipment and reduce pressure drop at various locations in the air distribution system. This results in lower noise pollution.

Type of Change

The change would modify an existing prescriptive requirement. The prescriptive requirements define the baseline building used in performance calculations, but are not mandatory.

Measure Availability and Cost

VSDs have been available for more than 20 years, and the latest generation is considered highly reliable. The equipment is common and available from multiple manufacturers at competitive prices. Furthermore, HVAC system designers and contractors have become more familiar with the technologies, realizing the proven reliability and reduced operating costs. Most new and retrofit VAV systems already use VSDs, as opposed to discharge dampers or inlet vane dampers.

Given the lead-time between adoption and enforcement, the manufacturers should be capable of meeting any equipment modifications and demand. For built-up VAV systems, there would not be any additional changes in accommodating VSDs and controls. For packaged type VAV systems, HVAC unit manufacturers would need to re-engineer their cabinets to accommodate the VSD and get UL listings.

Useful Life, Persistence and Maintenance

The reliability of VSDs has increased dramatically over the past 10-15 years and continues to increase with new technologies. The most recent advances in drive technology use third generation Insulated Gate Bipolar Transistors (IGBTs), which provide fast, accurate electronic signals to the motor and quieter operation. The IGBTs control the switching on the three terminals of an alternating current (AC) motor to achieve the required voltage and frequency expected of the motor. The energy savings of the VSD are persistent for the life of the equipment. The current generation of drives, have a design life of 10-15 years, which means that for the 15-year study period of life-cycle cost analysis, no replacements need to be considered. Should a drive fail, it is generally replaced with a new VSD due to the minimal cost of the drive as compared to the labor for VSD repairs. Furthermore, VSD costs are continuing to decline making replacements even more likely.

A VSD reduces mechanical stress on the motor drive through variable speed and soft starts. A soft start allows a motor to start at a reduced speed as opposed to single speed motors, which start abruptly and subject the motor to a high starting torque and to current surges that are up to 10 times the full load current. This reduced speed lessens mechanical and electrical stress, which will reduce maintenance costs and extend the life of the motor and drive equipment (bearings and belts). The maintenance of VSDs consists of blowing out components with dry air or nitrogen and tightening of bolts and screws.

One of the effects VSDs have on a building is power line harmonic distortion, which can effect sensitive electronic equipment, such as computers. These effects can be mitigated using filters in the VSDs or ahead of the power serving the HVAC equipment motor control center.

Performance Verification

The installation and commissioning of VSDs are not much different than other types of VAV drives with the most critical aspects of commissioning as follows:

- Verification, to ensure the unit has been installed in accordance with the manufacturers' recommendations.
- The static pressure sensor is installed at a representative location, normally two-thirds of the way from the fan to the furthest discharge in the longest, main duct run, with the required set point specified by the HVAC engineer or balancing contractor.

Acceptance requirements should be developed for this new Title 24 requirement.

Analysis Tools

The DOE 2 building energy simulation program was used for modeling one high-rise and one low-rise office building in three different scenarios using VSDs, inlet vanes, and discharge outlet dampers for variable air volume control in the 16 California climate zones. Simulation results are shown in Table 4 through Table 7.

Relationship to other Measures

The Acceptance Requirements proposal should be updated to include this proposed change to the size threshold for VAV controls. A separate proposal to require electronically-commutated motors in series fan-powered terminal units modifies the same section of the standards and will require coordination.

Methodology

The methodology estimates the energy savings and cost premium for a variety of fan motor sizes. The present value of energy savings on a per horsepower basis varies somewhat with motor size, but the VSD costs are significantly larger for smaller motors.

Cost Premiums

The cost of a VSD varies with size, with larger sizes costing less per horsepower than smaller sizes. The installed cost, from Means Mechanical Cost Data, ranges from $2,769 for a 1 hp VSD to $6,865 for a 25 hp VSD (see Table 2). The VSD cost includes the VSD in a National Electrical Manufacturers Association (NEMA)

1 enclosure. The NEMA 1 enclosure is a general purpose indoor enclosure intended primarily to prevent accidental contact of personnel with the enclosed equipment wherever oil, dust, or water is not a problem. The net installed cost of the VSD is somewhat lower than the absolute cost, because of the cost savings associated with not needing the motor starter and damper with the VSD. The control costs and commissioning costs of a VSD are comparable to inlet vanes or discharge dampers.

Table 2 shows the cost estimates for four fan control options: a constant volume fan (i.e., no control), a VAV fan controlled with discharge dampers, a VAV fan controlled with inlet vanes, and a VAV fan controlled with a VSD. Data for a constant volume fan are provided for reference, since the motor is common to all the systems. Forward-curved centrifugal fans are assumed in all cases since this type is most common in the size ranges considered.

These VSD cost estimates are believed to be conservative. Conversations with VSD and HVAC unit manufacturers suggest that actual VSD costs are somewhat lower than used in this analysis.

Table 2 – Installed Costs

Motor Size	**Constant Volume (1)**	**Discharge Damper (2)**	**Inlet Vanes (3)**	**VSD (4)**
1 hp	$700	$850	$925	$2,769
2 hp	$700	$875	$963	$2,769
3 hp	$700	$900	$1,000	$2,769
5 hp	$700	$1,020	$1,180	$2,769
7.5 hp	$720	$1,070	$1,245	$3,786
10 hp	$720	$1,120	$1,320	$3,786
15 hp	$1,000	$1,420	$1,630	$4,407
20 hp	$1,000	$1,450	$1,675	$5,961
25 hp	$1,000	$1,500	$1,750	$6,865

(1) Cost for starter and NEMA 1 enclosure (Means Mechanical Cost Data).

(2) Cost for (1) plus discharge outlet damper and actuator motor (Means Mechanical Cost Data).

(3) Cost for (1) plus inlet vane damper and actuator motor (1.5 x Discharge Damper cost).

(4) Variable speed drive and NEMA 1 enclosure (Means Mechanical Cost Data).

Energy Savings

DOE2.1E simulations are used to produce hourly airflow data for two building types and for each of the 16 California climate zones. Those 32 sets of data are placed in a database where the hourly fan electric demand is calculated for each case using the same equations as those used in DOE2.1E to calculate fan power as a function of part load ratio. This database method is used so that the impact of varying fan-oversizing ratios can be estimated more easily. The performance comparison between the three different fan control methods is very sensitive to fan size. A larger fan operates at low flow for more hours, which leads to more savings for the variable speed drive option. DOE2.1E's sizing algorithm tends to overestimate the peak airflow requirement (fan peak airflow is higher than the actual maximum hourly airflow). As a result, DOE2.1E tends to overestimate the benefits of VSDs relative to discharge dampers or inlet vanes. To avoid this oversizing problem, we use the database calculation method and set the fan size to three different levels:

1. Fan size equal to actual peak airflow.
2. Fan size 10% larger than peak airflow.
3. Fan size 20% larger than peak airflow.

The simulation model includes a variable air volume system (VAVS) with minimum flow ratio of 30% on the VAV boxes. The supply air temperature is assumed to be "reset by warmest zone." This temperature control method leads to a greater number of hours operating at higher airflow fractions, resulting in a conservative estimate of VSD savings.

The two building types are high-rise (10 stories, 196,000 ft^2, each floor 140 ft by 140 ft) and low-rise (2 stories and 50,000 ft^2, each floor 100 ft by 250 ft). In both cases, the windows cover 30% of the wall area. The glass type, wall construction, and roof construction vary by climate zone and come from Title 24-2001 nonresidential prescriptive requirements. The lighting power is 1.2 W/ft^2 and miscellaneous indoor equipment is 0.75 W/ft^2. The analysis uses the "nonres" schedule in the Title 24 ACM Manual.

To determine savings based on motor size, the results for each of the two buildings are scaled to provide results for a range of motor sizes. The scaling process accounts for varying motor and drive efficiency (simulations assumed 90% motor efficiency and 100% VSD efficiency). Smaller motors have lower efficiency. Smaller motors also have lower VSD efficiency because energy consumed by the drive accounts for a larger fraction of the total energy. The adjustments used here are listed in Table 3. The effect of these adjustments is to decrease the VSD savings, especially for smaller motors.

Table 3 – Motor and Drive Efficiencies Used to Adjust Simulation Results Based on Motor Size

Motor Size (hp)	**VSD Efficiency (1)**	**Motor Efficiency (2)**
1	82.5%	82.5%
2	86.5%	84.5%
3	88.4%	85.5%
5	92.4%	87.5%
71/2	93.0%	88.5%
10	93.5%	89.5%
15	93.6%	90.3%
20	93.7%	91.0%
25	93.8%	91.7%
50	94.4%	93.0%
100	96.6%	94.1%

(1) Variable frequency drive efficiency at full load. Source: http://www.oit.doe.gov/bestpractices/energymatters/wint2002_ask.shtml.

(2) Source: ASHRAE Standard 90.1-1999, Table 10.2. For 4-pole, open motor.

VFD and Motor efficiencies for 2, 3, 71/2, 15 and 20 hp motors have been interpolated.

Table 4 and Table 5 show simulation results for the two building types with the three different fan control methods. Table 6 and Table 7 show the resulting life-cycle energy cost by motor size for inlet vanes and VSDs for the two building types. The present value of electricity is assumed to be $1.37 per kWh as described in the document *Life Cycle Cost Methodology, 2005 California Building Energy Efficiency Standards*, dated March 11, 2002.

The energy cost results are shown for the 10% oversizing case, because it is considered the appropriate case for cost effectiveness analysis. Similarly, the energy cost results for discharge dampers are omitted here for sake of simplicity, because inlet dampers are considered to be the appropriate base case for VSD life-cycle cost calculations. See the Cost Effectiveness section below for more discussion.

Table 4 – Simulation Results for Low-rise Building, 10% Oversized Fan

Climate Zone	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7	CZ 8	CZ 9	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
Peak airflow (cfm)	31,953	29,477	25,865	26,725	22,946	25,034	28,194	31,068	32,579	33,826	36,875	33,110	36,869	39,425	40,098	36,680
Peak airflow (cfm/ft^2)	0.6	0.6	0.5	0.5	0.5	0.5	0.6	0.6	0.7	0.7	0.7	0.7	0.7	0.8	0.8	0.7
Fan power (bhp)	27	25	22	23	20	21	24	27	28	29	32	28	32	34	34	31
Fan kWh-yr, DD	45,482	47,863	44,850	47,126	45,191	46,025	47,354	49,656	51,723	52,046	52,891	50,180	55,394	56,220	61,821	52,119
Fan kWh-yr, IV	27,318	30,163	28,811	30,812	31,334	30,763	30,242	31,357	32,671	32,699	32,931	31,188	35,306	35,704	40,414	32,116
Fan kWh-yr, VSD	16,989	21,584	21,739	23,642	25,960	24,357	22,290	22,193	23,008	22,404	21,103	20,984	23,890	23,025	28,270	20,266
Fan kWh/hp-yr, DD	1,661	1,895	2,023	2,058	2,298	2,145	1,960	1,865	1,852	1,795	1,674	1,768	1,753	1,664	1,799	1,658
Fan kWh/hp-yr, IV	998	1,194	1,300	1,345	1,593	1,434	1,252	1,178	1,170	1,128	1,042	1,099	1,117	1,057	1,176	1,022
Fan kWh/hp-yr, VSD	620	854	981	1,032	1,320	1,135	922	833	824	773	668	739	756	681	823	645

Table 5 – Simulation Results for High-rise Building, 10% Oversized Fan

Climate Zone	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7	CZ 8	CZ 9	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
Peak airflow (cfm)	223,681	236,563	193,984	210,894	193,057	196,408	218,469	245,847	256,543	273,832	278,364	262,483	292,175	306,890	321,644	276,016
Peak airflow (cfm/ft^2)	1.1	1.2	1.0	1.1	1.0	1.0	1.1	1.3	1.3	1.4	1.4	1.3	1.5	1.6	1.6	1.4
Fan power (bhp)	192	203	166	181	165	168	187	211	220	235	239	225	250	263	276	237
Fan kWh-yr, DD	352,682	377,795	354,565	374,771	360,457	362,945	372,725	392,285	409,180	415,755	416,168	398,400	442,101	445,541	493,977	409,658
Fan kWh-yr, IV	216,851	237,890	234,972	247,116	241,899	243,814	240,248	248,317	259,733	262,063	264,004	249,642	285,257	286,561	325,183	255,811
Fan kWh-yr, VSD	149,974	168,049	184,954	191,035	193,383	193,873	179,592	175,716	183,966	177,879	177,465	168,889	195,369	189,191	227,529	169,431
Fan kWh/hp-yr, DD	1,840	1,863	2,133	2,073	2,179	2,156	1,991	1,862	1,861	1,772	1,744	1,771	1,766	1,694	1,792	1,732
Fan kWh/hp-yr, IV	1,131	1,173	1,413	1,367	1,462	1,448	1,283	1,179	1,181	1,117	1,107	1,110	1,139	1,090	1,180	1,081
Fan kWh/hp-yr, VSD	782	829	1,112	1,057	1,169	1,152	959	834	837	758	744	751	780	719	825	716

Table 6 – Life-Cycle Energy Cost (Low-Rise Building), 10% Oversized Fan

Inlet Vanes	**CZ 1**	**CZ 2**	**CZ 3**	**CZ 4**	**CZ 5**	**CZ 6**	**CZ 7**	**CZ 8**	**CZ 9**	**CZ 10**	**CZ 11**	**CZ 12**	**CZ 13**	**CZ 14**	**CZ 15**	**CZ 16**
1 hp	$1,491	$1,784	$1,942	$2,011	$2,381	$2,143	$1,870	$1,760	$1,749	$1,686	$1,557	$1,643	$1,670	$1,579	$1,758	$1,527
2 hp	$2,911	$3,484	$3,793	$3,926	$4,650	$4,184	$3,652	$3,437	$3,415	$3,292	$3,041	$3,208	$3,261	$3,084	$3,432	$2,982
3 hp	$4,316	$5,166	$5,623	$5,820	$6,893	$6,203	$5,415	$5,095	$5,062	$4,880	$4,508	$4,755	$4,834	$4,572	$5,088	$4,420
5 hp	$7,028	$8,412	$9,157	$9,479	$11,226	$10,102	$8,818	$8,297	$8,244	$7,947	$7,342	$7,744	$7,872	$7,445	$8,286	$7,198
7.5 hp	$10,424	$12,476	$13,581	$14,057	$16,649	$14,982	$13,078	$12,306	$12,227	$11,786	$10,888	$11,484	$11,675	$11,041	$12,288	$10,675
10 hp	$13,743	$16,449	$17,905	$18,533	$21,951	$19,753	$17,242	$16,224	$16,120	$15,539	$14,355	$15,142	$15,393	$14,557	$16,201	$14,075
15 hp	$20,432	$24,455	$26,620	$27,554	$32,634	$29,368	$25,634	$24,121	$23,966	$23,102	$21,342	$22,511	$22,885	$21,643	$24,087	$20,925
20 hp	$27,032	$32,356	$35,220	$36,456	$43,178	$38,855	$33,916	$31,913	$31,709	$30,566	$28,237	$29,784	$30,279	$28,635	$31,869	$27,685
25 hp	$33,533	$40,136	$43,689	$45,222	$53,560	$48,199	$42,071	$39,587	$39,334	$37,916	$35,027	$36,946	$37,560	$35,520	$39,532	$34,343
Variable Speed Drive	**CZ 1**	**CZ 2**	**CZ 3**	**CZ 4**	**CZ 5**	**CZ 6**	**CZ 7**	**CZ 8**	**CZ 9**	**CZ 10**	**CZ 11**	**CZ 12**	**CZ 13**	**CZ 14**	**CZ 15**	**CZ 16**
1 hp	$1,124	$1,548	$1,777	$1,870	$2,391	$2,057	$1,671	$1,510	$1,493	$1,400	$1,210	$1,340	$1,370	$1,234	$1,490	$1,168
2 hp	$2,094	$2,884	$3,310	$3,484	$4,456	$3,832	$3,114	$2,813	$2,781	$2,609	$2,254	$2,496	$2,552	$2,300	$2,777	$2,176
3 hp	$3,036	$4,181	$4,799	$5,052	$6,461	$5,556	$4,515	$4,079	$4,033	$3,782	$3,268	$3,619	$3,700	$3,335	$4,026	$3,155
5 hp	$4,730	$6,515	$7,478	$7,871	$10,066	$8,657	$7,034	$6,356	$6,284	$5,893	$5,092	$5,639	$5,765	$5,196	$6,273	$4,916
7.5 hp	$6,970	$9,599	$11,019	$11,598	$14,832	$12,755	$10,365	$9,365	$9,259	$8,683	$7,503	$8,308	$8,495	$7,657	$9,243	$7,243
10 hp	$9,141	$12,588	$14,450	$15,209	$19,451	$16,727	$13,592	$12,281	$12,142	$11,387	$9,839	$10,896	$11,140	$10,041	$12,121	$9,499
15 hp	$13,575	$18,695	$21,459	$22,587	$28,887	$24,842	$20,186	$18,239	$18,032	$16,911	$14,612	$16,181	$16,545	$14,912	$18,001	$14,107
20 hp	$17,942	$24,709	$28,362	$29,853	$38,178	$32,832	$26,679	$24,106	$23,832	$22,351	$19,312	$21,386	$21,867	$19,708	$23,791	$18,645
25 hp	$22,232	$30,618	$35,144	$36,992	$47,308	$40,684	$33,059	$29,870	$29,531	$27,695	$23,930	$26,500	$27,096	$24,421	$29,480	$23,103

Table 7 – Life-Cycle Energy Cost (High-Rise Building), 10% Oversized Fan

Inlet Vanes	**CZ 1**	**CZ 2**	**CZ 3**	**CZ 4**	**CZ 5**	**CZ 6**	**CZ 7**	**CZ 8**	**CZ 9**	**CZ 10**	**CZ 11**	**CZ 12**	**CZ 13**	**CZ 14**	**CZ 15**	**CZ 16**
1 hp	$1,691	$1,754	$2,112	$2,043	$2,185	$2,165	$1,918	$1,761	$1,766	$1,669	$1,654	$1,659	$1,703	$1,628	$1,763	$1,616
2 hp	$3,301	$3,424	$4,125	$3,990	$4,267	$4,227	$3,745	$3,439	$3,448	$3,259	$3,230	$3,239	$3,325	$3,180	$3,443	$3,156
3 hp	$4,894	$5,076	$6,115	$5,915	$6,325	$6,266	$5,551	$5,099	$5,111	$4,831	$4,788	$4,801	$4,928	$4,714	$5,104	$4,678
5 hp	$7,970	$8,267	$9,958	$9,633	$10,301	$10,205	$9,041	$8,304	$8,323	$7,868	$7,797	$7,819	$8,026	$7,676	$8,311	$7,619
7.5 hp	$11,820	$12,261	$14,768	$14,286	$15,277	$15,135	$13,408	$12,315	$12,344	$11,668	$11,563	$11,596	$11,903	$11,385	$12,326	$11,300
10 hp	$15,584	$16,165	$19,471	$18,835	$20,141	$19,954	$17,677	$16,236	$16,275	$15,384	$15,245	$15,288	$15,694	$15,010	$16,252	$14,898
15 hp	$23,169	$24,032	$28,948	$28,003	$29,945	$29,667	$26,281	$24,138	$24,196	$22,871	$22,666	$22,729	$23,332	$22,315	$24,161	$22,149
20 hp	$30,654	$31,797	$38,300	$37,050	$39,619	$39,251	$34,772	$31,937	$32,013	$30,260	$29,988	$30,072	$30,871	$29,525	$31,967	$29,305
25 hp	$38,025	$39,443	$47,510	$45,959	$49,146	$48,689	$43,133	$39,617	$39,710	$37,537	$37,199	$37,304	$38,294	$36,624	$39,654	$36,351
Variable Speed Drive	**CZ 1**	**CZ 2**	**CZ 3**	**CZ 4**	**CZ 5**	**CZ 6**	**CZ 7**	**CZ 8**	**CZ 9**	**CZ 10**	**CZ 11**	**CZ 12**	**CZ 13**	**CZ 14**	**CZ 15**	**CZ 16**
1 hp	$1,417	$1,502	$2,015	$1,915	$2,117	$2,086	$1,738	$1,511	$1,516	$1,373	$1,348	$1,360	$1,413	$1,303	$1,495	$1,298
2 hp	$2,641	$2,798	$3,755	$3,568	$3,945	$3,888	$3,238	$2,815	$2,824	$2,558	$2,511	$2,534	$2,633	$2,428	$2,786	$2,418
3 hp	$3,829	$4,057	$5,445	$5,173	$5,720	$5,637	$4,694	$4,081	$4,095	$3,709	$3,641	$3,674	$3,818	$3,520	$4,040	$3,505
5 hp	$5,965	$6,320	$8,483	$8,059	$8,912	$8,782	$7,314	$6,359	$6,380	$5,780	$5,672	$5,725	$5,949	$5,485	$6,294	$5,462
7.5 hp	$8,790	$9,313	$12,500	$11,875	$13,132	$12,941	$10,777	$9,370	$9,401	$8,516	$8,358	$8,435	$8,766	$8,082	$9,274	$8,047
10 hp	$11,527	$12,213	$16,392	$15,573	$17,221	$16,970	$14,133	$12,288	$12,328	$11,168	$10,960	$11,062	$11,496	$10,599	$12,162	$10,553
15 hp	$17,119	$18,138	$24,344	$23,128	$25,576	$25,203	$20,989	$18,249	$18,309	$16,586	$16,278	$16,428	$17,073	$15,740	$18,061	$15,673
20 hp	$22,626	$23,972	$32,174	$30,568	$33,802	$33,310	$27,740	$24,119	$24,199	$21,921	$21,514	$21,713	$22,564	$20,803	$23,871	$20,714
25 hp	$28,036	$29,704	$39,869	$37,877	$41,886	$41,275	$34,374	$29,887	$29,985	$27,163	$26,658	$26,905	$27,960	$25,778	$29,580	$25,668

Cost Effectiveness

VSD control is considered to be cost effective when the present value of energy cost savings is greater than the incremental installation cost. Figure 4 shows that savings exceed costs for the low-rise building for motor sizes 10 hp and larger in all climate zones. For many climate zones, VSDs are also cost effective for 5 and 7.5 hp motors. Figure 5 shows the high-rise building results, where VSDs are slightly more cost effective. However, the conclusion is the same: VSDs are cost effective in all climate zones for motors 10 hp and larger. VSDs for motors as small as 5 hp are cost effective in many climate zones.

These results compare VSD control to inlet vane control. VSDs would look more cost effective if compared to discharge dampers, but inlet vanes are considered to be a more appropriate base case because results show that inlet vanes are far more cost effective than discharge dampers for all motor sizes. So the results here show the cost effectiveness of the additional investment and savings for VSDs compared to inlet vanes.

VSDs are least cost effective in the coastal climate zones 5 and 6. Buildings in these climates have cooling loads that are less variable than in other parts of the state. They tend to have lower peak load and operate more hours at close to that peak load. Savings are also lower in bay area climate zones 3 and 4. If these climate zones (3 through 6) are ignored, then VSDs are cost effective down to 5 hp.

Table 8 and Table 9 list the net life-cycle savings that are plotted in Figure 4 and Figure 5. These values are the present value of energy savings, calculated at $1.37 per kWh, minus the incremental VSD cost from Table 2.

As mentioned in the Energy Savings section above, savings results are sensitive to fan oversizing assumptions. If fans are larger than actual peak airflow, then the savings for using VSD fan control are greater. Energy savings were calculated assuming 0%, 10% and 20% oversizing to investigate sensitivity of cost effectiveness results. At 0% oversizing, there are a few cases (climate zones 3, 5, and 6) where the cost effectiveness threshold increases to 15 hp. With 20% oversizing, the threshold drops to 5 hp for all cases, except the low-rise building in climate zone 5. Figure 4, Figure 5, Table 8, and Table 9 below list the 10% oversizing results, where all climate zones meet the 10 hp threshold. The 10% results have been chosen as the basis for recommendations because they are considered to be closer to actual design practice while still being conservative.

Note that these results are based on a typical workday occupancy schedule. VSDs on VAV fans operating continuously are likely to be more cost effective because airflow requirements are usually lower at night (when loads are lower).

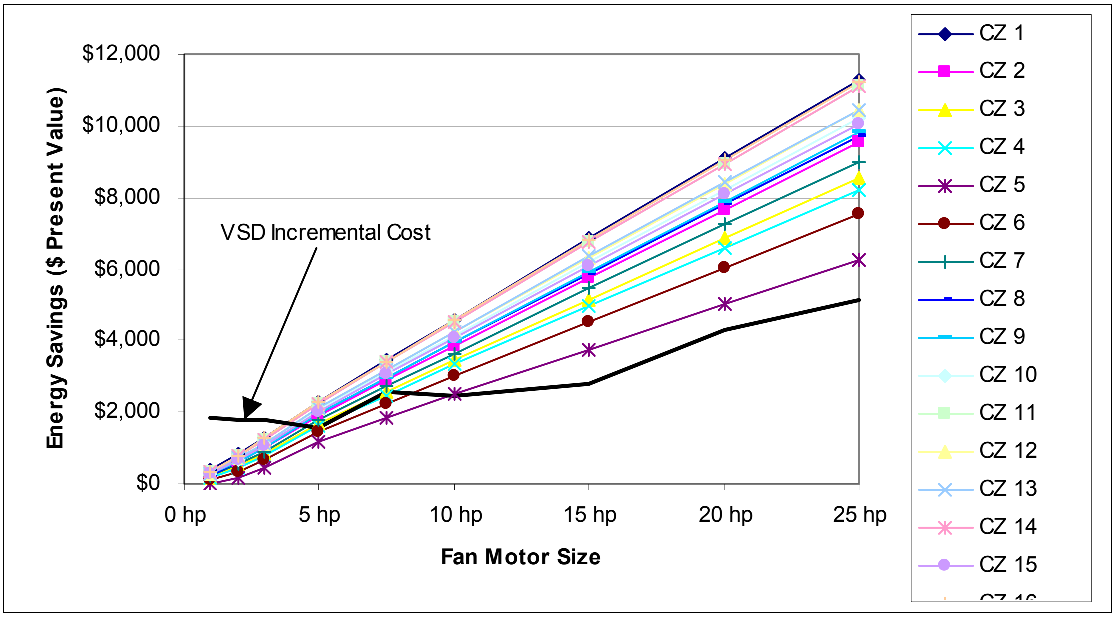

Figure 4 – Energy Savings for VSD vs. Inlet Vanes, Low-Rise Building, 10% Oversizing

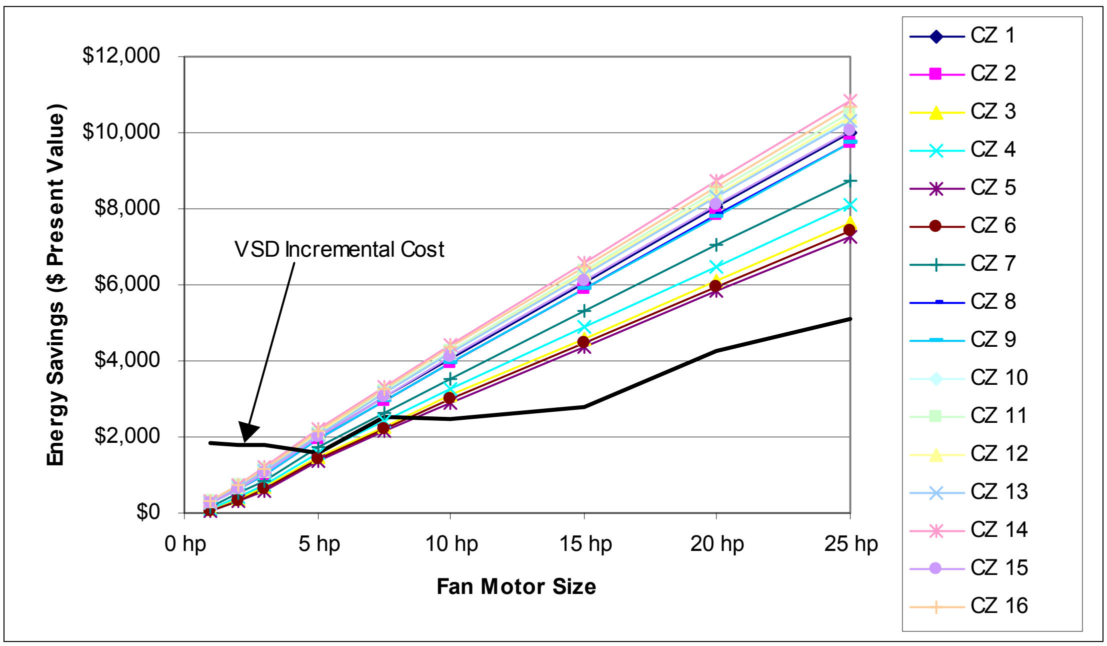

Figure 5 – Energy Savings for VSD vs. Inlet Vanes, High-Rise Building, 10% Oversizing

Table 8 – Net Life Cycle Savings (Low-Rise Building) VSD vs. Inlet Vanes, 10% Oversized Fan

	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7	CZ 8	CZ 9	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
1 hp	($1,477)	($1,607)	($1,678)	($1,703)	($1,854)	($1,758)	($1,645)	($1,594)	($1,588)	($1,558)	($1,496)	($1,541)	($1,544)	($1,499)	($1,577)	($1,485)
2 hp	($989)	($1,205)	($1,323)	($1,364)	($1,612)	($1,453)	($1,267)	($1,183)	($1,173)	($1,123)	($1,019)	($1,094)	($1,097)	($1,022)	($1,151)	($1,001)
3 hp	($489)	($785)	($946)	($1,001)	($1,336)	($1,122)	($869)	($753)	($740)	($671)	($529)	($633)	($635)	($532)	($707)	($504)
5 hp	$709	$309	$90	$19	($429)	($143)	$195	$353	$372	$465	$661	$516	$518	$660	$424	$693
7.5 hp	$912	$336	$21	($82)	($724)	($314)	$172	$400	$427	$562	$845	$635	$639	$844	$505	$891
10 hp	$2,136	$1,394	$990	$858	$34	$560	$1,184	$1,477	$1,513	$1,686	$2,050	$1,780	$1,787	$2,051	$1,615	$2,110
15 hp	$4,079	$2,982	$2,383	$2,189	$971	$1,749	$2,671	$3,105	$3,157	$3,414	$3,953	$3,553	$3,563	$3,954	$3,309	$4,041
20 hp	$4,805	$3,360	$2,572	$2,317	$713	$1,737	$2,951	$3,522	$3,591	$3,929	$4,639	$4,112	$4,126	$4,641	$3,791	$4,755
25 hp	$6,185	$4,403	$3,429	$3,115	$1,137	$2,400	$3,897	$4,602	$4,688	$5,105	$5,982	$5,330	$5,349	$5,984	$4,936	$6,124

Table 9 – Net Life Cycle Savings (High-Rise Building) VSD vs. Inlet Vanes, 10% Oversized Fan

	CZ 1	CZ 2	CZ 3	CZ 4	CZ 5	CZ 6	CZ 7	CZ 8	CZ 9	CZ 10	CZ 11	CZ 12	CZ 13	CZ 14	CZ 15	CZ 16
1 hp	($1,571)	($1,592)	($1,747)	($1,715)	($1,776)	($1,766)	($1,664)	($1,593)	($1,594)	($1,548)	($1,538)	($1,546)	($1,555)	($1,519)	($1,576)	($1,525)
2 hp	($1,145)	($1,180)	($1,436)	($1,384)	($1,484)	($1,467)	($1,299)	($1,182)	($1,183)	($1,106)	($1,087)	($1,102)	($1,115)	($1,054)	($1,149)	($1,068)
3 hp	($704)	($749)	($1,099)	($1,027)	($1,164)	($1,139)	($912)	($752)	($753)	($647)	($622)	($642)	($659)	($576)	($705)	($596)
5 hp	$416	$358	($114)	($15)	($200)	($166)	$138	$355	$354	$499	$536	$505	$488	$602	$429	$569
7.5 hp	$489	$407	($272)	($130)	($396)	($347)	$90	$404	$402	$611	$664	$619	$596	$762	$511	$711
10 hp	$1,591	$1,486	$613	$796	$454	$518	$1,078	$1,482	$1,480	$1,750	$1,819	$1,760	$1,732	$1,945	$1,624	$1,879
15 hp	$3,273	$3,118	$1,827	$2,098	$1,592	$1,687	$2,515	$3,112	$3,109	$3,509	$3,611	$3,524	$3,483	$3,798	$3,323	$3,699
20 hp	$3,742	$3,539	$1,840	$2,196	$1,531	$1,656	$2,745	$3,532	$3,528	$4,054	$4,189	$4,074	$4,020	$4,435	$3,810	$4,304
25 hp	$4,874	$4,623	$2,526	$2,967	$2,145	$2,299	$3,644	$4,615	$4,610	$5,259	$5,426	$5,284	$5,218	$5,731	$4,959	$5,568

Recommendations

This proposal is to reduce the size threshold for VSD requirements from "larger than 25 hp" to "10 hp or larger" for VAV systems.

Proposed Standards Language

The specific proposed language revisions to §144 – Prescriptive Requirements for Space Conditioning Systems are as follows:

(c) **Power Consumption of Fans.** Each fan system used for comfort space conditioning ~~with a total fan power index over 25 horsepower~~ shall meet the requirements of Item 1 or 2 below, as applicable. Total fan system power demand equals the sum of the power demand of all fans in the system that are required to operate at design conditions in order to supply air from the heating or cooling source to the conditioned space, and to return it back to the source or to exhaust it to the outdoors; however, total fan system power demand need not include the additional power demand caused solely by air treatment or filtering systems with final pressure drops more than one-inch water column (only the energy accounted for by the amount of pressure drop that is over one inch may be excluded), or fan system power caused solely by process loads.

1. **Constant volume fan systems.** The total fan power index <u>at design conditions</u> of each fan system ~~at design conditions~~ <u>with total horsepower over 25 horsepower</u> shall not exceed 0.8 watts per cfm of supply air.

2. **Variable air volume (VAV) systems.**

   A. The total fan power index <u>at design conditions</u> of each fan system ~~at design conditions~~ <u>with total horsepower over 25 horsepower</u> shall not exceed 1.25 watts per cfm of supply air; and

   B. Individual VAV fans with motors ~~over 25 horsepower~~ <u>10 horsepower or larger</u> shall meet one of the following:

      i. The fan motor shall be driven by a mechanical or electrical variable speed drive.

      ii. The fan shall be a vane-axial fan with variable pitch blades.

      iii. For prescriptive compliance, the fan motor shall include controls that limit the fan motor demand to no more than 30% of the total design wattage at 50% of design air volume when static pressure set point equals 1/3 of the total design static pressure, based on certified manufacturer's test data.

3. **Air-treatment or filtering systems.** For systems with air-treatment or filtering systems, calculate the adjusted fan power index using the following equation:

Adjusted fan power index = Fan power index x Fan adjustment

$$\text{Fan adjustment} = 1 - \left(\frac{SP_a}{SP_f}\right)$$

WHERE:

SP_a = Air pressure drop across the air-treatment or filtering system.

SP_f = Total pressure drop across the fan.

Bibliography and Other Research

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Hirsh, James J. & Associates. VSD Fan Control, California Building Energy Efficiency Standards – Revisions for July 2003 Adoption.

National Electrical Code.

Limitation of the Use of Lay-In Insulation in Nonresidential Buildings

Overview

Description

Approximately 75% of new retail construction makes use of dropped ceiling systems (T-bar and acoustical tile). At least 60% of ceiling area is directly below a roof and therefore, how well building components and energy consuming systems are integrated to configure the ceiling system is a serious issue that impacts the resultant building energy use. Currently, insulating either the ceiling or the roof deck is considered equivalent by the California Building Efficiency Standards. Acoustic ceiling/lighting design affects fire protection, seismic safety, lighting, daylighting, insulation, mechanical systems, and acoustics. Research indicates that approximately 5-10% of acoustic tile t-bar ceilings have lay-in insulation on top of them. Insulation on t-bar ceilings creates two major problems. During building renovation, insulation on the t-bar ceiling is usually moved around and not consistently put back in place properly. Another problem with lay-in insulation at the t-bar is high ceiling air leakage. The analysis contained in this proposal indicates that laying insulation on top of an acoustic tile ceiling is not equivalent to insulating the roof deck of commercial buildings. Furthermore, this report shows that insulating the roof deck and the sidewalls of the plenum below the roof deck instead of laying insulation directly on a t-bar ceiling is clearly cost-effective when amortized over the course of 30 years when the plenum heights are less than 12 feet tall. It is proposed, therefore, to restrict the use of insulation on ceilings, except for cases where the plenum space between the ceiling and roof exceeds 12 feet in height. .

Benefits

Installing insulation at the roof deck instead of on top of ceilings saves heating and cooling energy and peak electrical demand. Since the scope of the proposal is to recommend measures that are cost-effective, there is a net monetary savings. This measure also reduces the negative effect of leaking HVAC ducts so, to an extent, this measure increases the energy efficiency of the HVAC system over the life of the building.

Environmental Impact

Besides the positive environmental aspects of saving heating and cooling energy, insulating the roof deck avoids the problem of insulation being disturbed when the ceiling cavity is entered to perform maintenance or remodeling activities. This would reduce human exposure to the respiratory hazard of inhaling fiberglass fibers.

Type of Change

This proposal would specify insulation location under the prescriptive requirements in Section 143(a). As a mandatory measure this proposal would have no impact on the performance method calculations. However, since this proposal would still allow for insulated ceilings in some cases, the duct efficiency calculations will need to take into account insulation position. This is discussed in the duct sealing proposals for the 2005 Standards.

Technology Measures

This measure uses currently available roof deck insulation practices that apply to most commercial buildings. This measure would limit the use of lay-in insulation that is currently used in commercial buildings.

Measure Availability and Cost

Three options of insulating ceilings were explored and cost estimates were made. The options considered were rigid insulation above the roof deck, non-rigid insulation below the roof deck, lay-in insulation above acoustic tiles on t-bar ceilings, and lay-in insulation above sheetrocked ceilings. Interviews were made with contractors to get the latest pricing information along with labor costs for the various types of installations.

As a reference, the *RS Means Building Construction Cost Data, 15th Annual Edition, 2002 Western Edition*, was used as one source of pricing information.

The lookup tables in the Means Catalogue provide an average cost for specific insulation components. To make a sound comparison with the cost data obtained from the contractors, the data obtained from the lookup tables were adjusted using city cost indexes. Simple averages for the cities of Sacramento, Stockton, and Vallejo were used to get an average city adjustment index.

Data collected from both these sources is presented in the table below. Costs include material cost, installation cost, and contractor markup.

For evaluation of the cost effectiveness of a measure, the measure cost was taken to be the average of the RS Means costs and the costs from the contractor survey.

$$\text{Measure Cost} = \frac{\text{R.S. Means} + \text{Average from Phone Surveys}}{2}$$

Table 10 -- Costs of Insulation (including materials, labor and contractor markup) from RS Means Catalogue and Telephone Interviews with Contractors

	Means Catalogue	Average from Surveys
Suspended Acoustic Ceiling		
Mineral Fiber on 5/16" T bar suspension 2' x 2' x 3/4" lay-in board	3.46 $/SF	1.43 $/SF
2' x 4' x 5/8" tile	2.34 $/SF	1.35 $/SF
Fiberglass ceiling board, 2' x 2' x 3/4", plane faced	3.19 $/SF	1.65 $/SF
Offices, 2' x 4' x 5/8"	2.21 $/SF	1.57 $/SF
Vinyl Faced dry wall tile 2' x 2' tiles - can be used with t-bars		1.66 $/SF
2' x 4' tiles		1.55 $/SF
Laid-in Insulation		
Fiberglass, Kraft faced batts or blankets 6" tk, R19 23"wide	0.69 $/SF	0.45 $/SF
Foil faced	0.74 $/SF	0.79 $/SF
Unfaced	0.70 $/SF	0.43 $/SF
Below deck Insulation (Panalized 2x6 w/ 24 oc and 8' bays)		
Fiberglass, Kraft faced batts or blankets 6" tk, R19 23"wide	0.69 $/SF	
Foil faced	0.74 $/SF	0.69 $/SF
Unfaced	0.70 $/SF	0.43 $/SF
(Metal Deck using imapling pins)		
Fiberglass, Kraft faced batts or blankets 6" tk, R19 23"wide		0.79 $/SF
Foil faced		0.53 $/SF
Unfaced		
Below deck Insulation (Concrete Slab - Ins attached with glue pins)		
Fiberglass, Kraft faced batts or blankets 6" tk, R19 23"wide	0.69 $/SF	
Foil faced	0.74 $/SF	1.17 $/SF
Unfaced	0.70 $/SF	0.84 $/SF
Above deck insulation		
Extruded Polystyrene 15 PSI comp strength, 4" tk, R20	1.65 $/SF	1.50 $/SF
25 PSI	1.70 $/SF	1.55 $/SF
40 PSI	1.99 $/SF	
60 PSI	2.27 $/SF	
Polystyrene OR Polyiso 25 PSI 1" tk, R9		0.75 $/SF
IB System 100 - 3600 SF Project		3.60 $/SF
Above 3600 SF		2.75 $/SF
Dry Wall		
Framing only using hanging t-bars - Sheetrock is screwed onto it	2.08 $/SF	4.50 $/SF
+ taping	3.08 $/SF	5.50 $/SF
+ finishing and texture	3.28 $/SF	5.70 $/SF
Framing using studs spanning across walls. Max is 16ft. span		3.50 $/SF
Over 8' hight	Add 22c	
Side Wall Insulation		
Fiberglass, Kraft faced batts or blankets 6" tk, R11 23"wide	0.52 $/SF	
Foil faced	0.60 $/SF	
Unfaced	0.50 $/SF	
Side Wall Insulation (for CMU or tilt up walls)		
Using stick pins or Impaling pins, R-11 non rigid unfaced insulation		0.58 $/SF
Foil faced instead.		0.65 $/SF
Using furring, R-11 non rigid unfaced insulation		0.30 $/SF
Using furring, R-13 non rigid unfaced insulation		0.40 $/SF

Useful Life, Persistence and Maintenance

Telephone interviews were conducted with five architects from firms that are involved in design of commercial buildings in California. Questions were asked about useful life, persistence, and maintenance of insulation.

The interviewees were asked to rank the following three insulation types in terms of longevity. The answers are presented in a matrix below. Only two of the architects answered this set of questions. Only two of the architects felt they were informed enough to given an opinion of the longevity of insulation in different locations.

The interviewee I2 mentioned the reason for his ranking order is that since there is less access to insulation under the deck, they tend to last longer (about 40 years). Insulation on the roof is more susceptible to leaks and repairs so they may not last as long (about 20 years). Lay-in insulation on the other hand can get knocked off by anyone trying to access the plenum space for duct or cabling work (about 12 years before they need reworking if not replacing).

Interviewee I3 mentioned that lay-in insulation gets removed and shifted by people accessing the plenum for duct and ceiling work. Roof insulation ages due to walking on the roof, water leakage, etc.

This study is based on a 30-year useful life for insulation on roof decks, drywall ceilings, and t-bar ceilings.

Table 11 -- Architects' Ranking of Insulation Longevity

	Interviewee 2		Interviewee 3	
	Ranking	Life	Ranking	Life
Rigid insulation on top of deck	2	20 yrs	1	40 yrs
Non-rigid insulation under the roof deck	1	40 yrs	N/A	N/A
Lay-in insulation on top of acoustic tile	3	12 yrs	2	10 yrs

The interviewees were asked to rank the following three insulation types in terms of ease of installation. The answers are presented in a matrix below.

Table 12 -- Architects' Ranking Based on Ease of Installing Insulation Types

	Interview 1	Interview 4	Interview 5
Rigid insulation on top of deck	3	2	1
Non-rigid insulation under the roof deck	2	2	3
Lay-in insulation on top of acoustics	1	1	2

Interviewee I4 mentioned that in retrofit projects, rigid insulation is favored, only if the roof is being redone. If not, then lay-in insulation is a better choice.

The interviewees were asked to identify problems of maintenance with the different types of insulation.

The most commonly mentioned problem for lay-in insulation was that of maintenance. The insulation gets knocked off by people reaching into the plenum space for ducting and cabling work.

It was also mentioned that if it was known that the building will be occupied by other tenants over time, lay-in insulation was not preferred, as it is common to change the acoustic ceiling when new occupants move in. In these cases, insulation at the roof deck was preferred.

It was mentioned that it is difficult to replace rigid insulation on top of the roof deck. A built-up or membrane roof would have to be ripped off to access the rigid insulation. Similarly, if the roofing needs to be replaced, the rigid insulation also has to be replaced.

Performance Verification

The value of insulation is very dependent on the quality of its installation. This proposal focuses on changing the requirements for where insulation is placed and is not suggesting changes in how installation quality is assured.

Cost Effectiveness

The measure proposed is cost-effective. Cost effectiveness is shown in this proposal by comparing the incremental cost of insulating the roof deck instead of placing insulation on top of the acoustic ceiling tiles using the time dependent valuation (TDV) approach.

Analysis Tools

As a prescriptive measure, no analysis tools would be necessary. An important aspect of the analysis in this study is the modeling of duct leakage regain with respect to different ceiling types.

Relationship to Other Measures

The amount of heat transfer across the ceiling plane has a significant impact on the "regain" or the heat lost from ducts that is subsequently recovered as this heat migrates back across the ceiling into the conditioned space. If ducts are leaking into the plenum space, the cost effectiveness of tightening these ducts is substantially higher if the plenum is ventilated and the insulation is installed at the ceiling. When lay-in insulation is used both of these conditions are present.

The benefit of placing insulation at the roof deck is substantially greater with leaky ducts. When the ducts are leaking in the plenum, the plenum essentially becomes a conditioned space. If the ducts are not leaking then the space is indirectly conditioned through the uninsulated ceiling, and the temperature difference between the plenum and the outdoors is reduced. This reduces heat transfer from the building to the outside as compared to the case with leaky ducts.

Background

The information needed to perform the analysis of the effectiveness of lay-in insulation came from an earlier phase of the PIER project as well as from research carried out on other projects. Since energy impacts of lay-in insulation is dependent upon other components of the building envelope and mechanical systems, much of this work was performed in conjunction with parallel research on the value of sealing ducts in small nonresidential buildings being completed for separate 2005 standards change proposals.

Phone Interviews

To better understand the prevalence of the use of lay-in insulation, 200 building managers were contacted and interviewed about the presence of lay-in insulation in their buildings. A prior report on this project goes into the details of the phone interviews.[3]

The following conclusions were drawn from these interviews.

- Over half of the buildings in the sample were reported to have dropped ceilings (57%).
- Only 5% of the buildings with dropped ceilings were thought to have lay-in insulation. The PIER light commercial HVAC research project found a similar percentage (10%) of buildings having lay-in insulation.[4]

Site Surveys

The phone interviews identified buildings with lay-in insulation. Building managers of the buildings with lay-in insulation were asked to allow a survey team to observe and record the fraction of ceiling area that was actually covered with lay-in insulation. Additional buildings were also identified from other site surveys funded by another PIER project or by the California utilities as part of their efficiency programs. Site surveys were performed on 13 nonresidential buildings with surveyors taking a total of 36 observations above the acoustic ceiling tiles. Each observation included opening up a ceiling tile, peering up into the plenum, visually identifying what fraction of observable ceiling area is covered with insulation and measuring temperatures in the plenum. The fraction of insulation coverage is illustrated in Figure 6 for buildings of various ages

[3] *Lay-In Insulation Telephone Survey Procedure*. See References for full citation.

[4] Prior work by LBNL (Delp et al) had found that 50% of light commercial buildings had lay-in insulation. Mark Modera conducted an informal survey of HVAC contractors – they reported a high fraction of buildings with lay-in insulation. The discrepancy of lay-in insulation frequency may be due to the vintage of buildings. The buildings in the PIER studies were constructed or remodeled within the last five years.

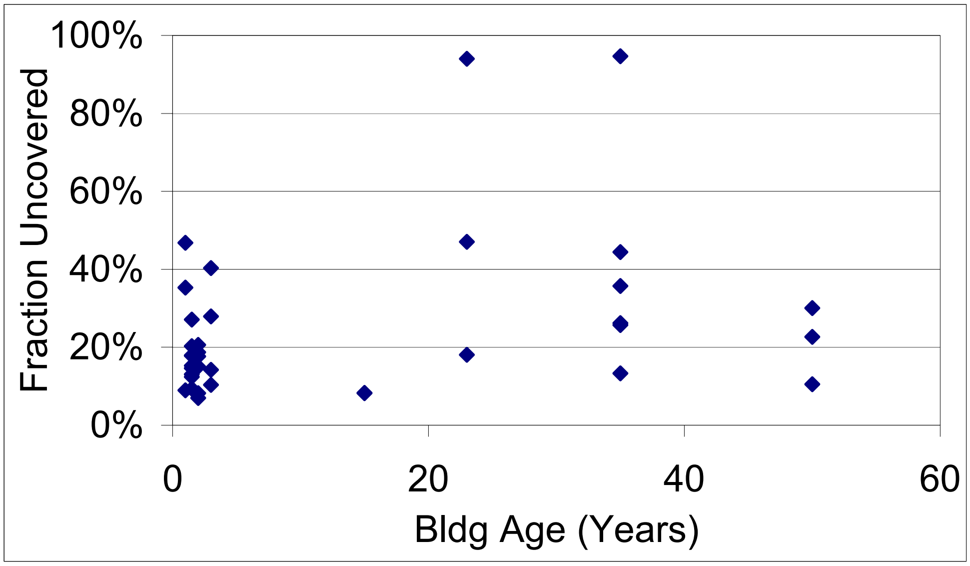

Figure 6 -- Fraction of Ceiling Uninsulated Compared to Building Age

The following conclusions have been drawn from the data in Figure 6.

- If the two observations with over 90% of the ceiling uninsulated are eliminated, essentially no correlation exists between building age and fraction of the ceiling that is uncovered. New buildings perform essentially the same as old buildings in this respect.
- Most of the data falls between 10% uncovered and 45% uncovered.
- When only 10% of the ceiling area is uncovered, all of the recessed troffers were uncovered, but all of the tiles were covered. These troffers should be uncovered because they are not designed to be insulated and may overheat or catch fire if they are covered with insulation.

Ceiling Air Leakage

The intent of this project is to analyze the energy consequences of lay-in insulation over t-bar ceilings. One of the most important factors in this analysis is the impact of air leakage through the t-bar ceiling.

- This study made use of the ceiling air leakage results from research done by the Florida Solar Energy Center.[5] Other data sources given below were considered but were not used for the calculations in this report because they were not published and subjected to peer review; were not studies of actual installations; or were not clearly relevant to installed t-bar ceilings in the U.S.
- An in-house study conducted by Armstrong World Industries in a test cell of four 2 ft by 2 ft acoustic ceiling tiles. A differential pressure of 0.5 inches of water column (125 Pa) was created across the ceiling plane and the flow rates measured. Also measured were the leakage of a 2 ft by 2 ft lensed fluorescent fixture and a recessed can. This study is unpublished, and therefore has not been subjected to peer review. It also is a laboratory study of optimal installation of ceiling tiles that is not likely to be representative of actual installations observed by field researchers.
- The 2001 ASHRAE Handbook of Fundamentals “Residential Air Leakage” section has a table of effective leakage areas for a variety of building components at a reference pressure of 4 Pascals.[6] The value for a

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[5] Cummings J B, Withers C.R. 1998. “Building cavities used as ducts: air leakage characteristics and impacts in light commercial buildings” ASHRAE Trans. Cummings, J.B., Withers, C.R., 2000. “Best Practices for the Location of the Air and Thermal Boundaries in Small Commercial Buildings.” Proceedings of 12th Annual Symposium on Improving Building Systems in Hot and Humid Climates, San Antonio, TX, May 2000.

[6] p. 26.15, Table 1, Effective Air Leakage Areas (Low-Rise Residential Apllications Only), 2001 ASHRAE Handbook of Fundamentals

dropped ceiling is 10 times lower than the value for a "general ceiling." The value for the "general ceiling" is similar to the data collected by Armstrong World Industries. This table is labeled "low rise residential applications only," and there is no clarification regarding what is meant by "dropped ceiling" or "general ceiling," or any reference to the source of the values in the table. If "dropped ceiling" is intended to represent t-bar ceilings, and "general ceiling" is intended to represent sheet rocked ceilings, then the values in the table make no sense. One possible explanation is that the values are reversed. Another possible explanation is that "dropped ceilings" in residential buildings are sheet rocked ceilings that are lower than the main ceiling, which is common for closets and hallways. Perhaps the "dropped ceilings" are more likely to have surface-mounted lighting fixtures and fewer penetrations than "general ceilings." It is possible that the data comes from studies in Europe where buildings are tighter and construction patterns are different. Without substantially better information, this data cannot be applied to actual installations of t-bar ceilings in commercial buildings in the U.S.

- Field studies by the Lawrence Berkeley National Laboratory have concluded that t-bar ceilings are quite leaky.[7]

The leakage values of the ceiling from different sources were presented in different formats: effective leakage area (reference pressure of 4 Pa), cfm at 50 Pascal, and cfm at 25 Pascal differential pressure.

To maintain a consistent reporting format, this information is converted into an effective leakage area, A_{r1} (in^2), at the reference pressure of 4 Pa (0.016 in WC) using the following formula.[8]

$$A_{r1} = \frac{Q_{r2}}{C_6 \; C_D \; \sqrt{\frac{2}{\rho}} \; (\Delta P_{r1})^{0.5-n} \; (\Delta P_{r2})^{n}}$$

where,

Q_{r2}	=	flow rate at pressure difference ΔP_{r2}, cfm
C6	=	conversion unit factor = 5.39
CD	=	coefficient of discharge = 1.0
ρ	=	density of air, 0.075 lb_m/ft^3
ΔP_{r1}	=	reference pressure differential, 0.016 in WC
ΔP_{r2}	=	pressure differential at alternate pressure, ___ in WC
n	=	pressure exponent, 0.65

Table 13 provides the infiltration rates that are quoted by different sources and places them into consistent units, either the effective leakage area or the flow rate at the reference pressure of 4 Pascals. As will be discussed later, we evaluated the infiltration flows across the ceiling plane at even lower differential pressures than the 4 Pascal "reference pressure." The FSEC values for the effective leakage area of ceiling components were used for calculation for this study.

[7] Delp, W. W., Matson, N. E., Tschudy, E., Modera, M.P. and Diamond, R.C. "Field Investigation of Duct System Performance in California Light Commercial Buildings," Lawrence Berkeley National Laboratory, Publication 40102.

[8] Accomplished by rewriting Equation 35 and solving for A_{r1} p. 26.13 2001 ASHRAE Fundamentals.

Table 13 -- Effective Leakage Area of Ceiling Components from Various Sources

	Quoted Values				
Source	**CFM/sf**	**Pressure (Pa)**	**CFM/sf @4 Pa**	**ELA**	**Units**
Armstrong Ceilings Tile	0.60	124.5	0.0642	0.0182	in2/sf
Armstrong Ceilings Lights	3.00	124.5	0.3211	0.0910	in2/sf
Armstrong Combined	0.84	124.5	0.0899	0.0255	in2/sf
FSEC(1)	**3.70**	**25**	**1.1243**	**0.3187**	**in2/sf**
FSEC(2)	**5.50**	**50**	**1.0651**	**0.3019**	**in2/sf**
ASHRAE Ceiling General			0.0915	0.0260	in2/sf
ASHRAE Ceiling Dropped			0.0095	0.0027	in2/sf
ASHRAE recessed lights			5.6302	1.6000	in2/ea
ASHRAE for 2' by 2' light			1.4075	0.4000	in2/sf
UBC 1/150 free area roof			3.3781	0.9600	in2/sf

Heat Loss From Luminaires

One of the criteria for building the simulation model for the study was to account for heat loss from the luminaires and where the heat generated from electric lighting goes, which depends upon how the luminaires are mounted. In the first case study (see section Mass Building With Troffers), the models have two mounting configurations for fluorescent luminaires. Buildings that had drywall ceilings were modeled with surface-mounted luminaires. Buildings with t-bar ceilings were modeled with recessed troffers. In the second and third case studies (see sections Mass Building With Troffers and Mass Building with Pendant Lighting), the models use pendant lighting on ceilings. Estimates of the fraction of heat flow from electric lighting into the plenum were obtained from Lithonia Lighting for the major classes of fluorescent luminaires. This split of lighting heat between the conditioned space and plenum is given in Table 14.

Table 14 -- Fraction of Electric Lighting Heat to Occupied Space and Ceiling Cavity

Luminaire Mounting	Occupied Space	Ceiling Cavity
Ceiling Surface Mount	90%	10%
Pendant	100%	0%
Recessed Static	70%	30%
Recessed Heat Extract	35%	65%

Thus, the models of buildings with t-bar ceilings and recessed static lighting would allocate 70% of the lighting power to the conditioned space and 30% to the plenum zone. The models of buildings with a drywall ceiling and surface-mounted lighting allocated 90% of the lighting heat gain to the conditioned space and just 10% to the plenum. The models with pendant lighting allocated 100% of the lighting heat gain to the conditioned space.

Methodology

Building Simulation Models

The following text describes the methodology used for DOE-2.2 simulation runs for comparing the energy impacts of various methods of insulating the roofs and ceilings of commercial buildings. The model used was created by Architectural Energy Corporation to investigate the impacts of duct leakage on small commercial building energy consumption for a separate 2005 standards change proposal. Given that insulation position affects the energy impacts of duct leakage and vice versa, the same building simulation model is used for this project.

Thus, the estimates about the energy trade-offs between “lay-in” insulation laid on top of acoustic ceiling tiles versus insulation installed on top or directly below the roof deck are correlated to the amount of duct leakage in the plenum.

The 2001 California Building Efficiency (Title 24) Standards based duct efficiency on seasonal multipliers on HVAC system efficiency derived from ASHRAE Standard 152. The analysis in this report uses time-dependent valuation (TDV), since the CEC staff has supported TDV for evaluation of cost effectiveness and for comparison of trade-offs in the performance method (Alternative Compliance Method or ACM) in the 2005 Title 24 standards. The impact of duct tightening is expected to vary as a function of time and temperature, thus a single value approach will tend to underestimate the impacts under peak conditions. It is necessary to evaluate the impacts of duct tightening on an 8,760 hourly basis to fully implement the TDV procedure.

Options for including duct tightening in Title 24 nonresidential compliance were examined by Franconi (CEC, 1999). The work focused on the issues related to modeling duct leakage in DOE-2.1E in large and small commercial buildings, and identified several shortcomings in the program related to duct leakage modeling. Despite these shortcomings, Franconi recommended using DOE-2 as the duct compliance tool based on the key role the program already plays in the nonresidential compliance process. Since the work was published, capabilities to model return side leakage and the ability to specify the source of the makeup air (either outdoors or a buffer zone containing the duct system) have been added to the DOE-2.2 program. Many of the remaining limitations are more critical for larger buildings with VAV systems that fall outside of the proposed duct sealing standards. A summary of the limitations cited by Franconi and comments reflecting more recent developments are shown in Table 15 below.

Table 15 -- Limitations of DOE-2 Models and Comments

Limitation	Comments
Savings not calculated for re-sizing fans after leakage sealing.	Not an issue in small buildings, since fan flows are generally not adjusted.
Leakage makeup air comes from ambient.	DOE-2.2 allows specification of a mixture of outdoor and return air as the source of the makeup air.
Conduction and leakage losses not modeled for return systems.	Return side leakage losses modeled using DOE-2.2; conduction losses are not.
Duct heat loss coefficients are constant, ignoring variations in loss coefficients as a function of air flow, radiation, and duct/ambient delta T.	Limitation still exists.
Fixed leakage rate assumption.	Appropriate for constant volume systems.
No explicit link between duct leakage and infiltration.	Limitation still exists, but not an issue for balanced supply and return leakage or low leakage rates.

To estimate the cost effectiveness of roof versus ceiling insulation and ceiling infiltration, a series of simulation studies are undertaken in conjunction with the research team that was investigating the cost effectiveness of duct tightening. First, a simple “box” prototype model is developed to test the capabilities and evaluate the response of the DOE-2.2 program to several duct efficiency and operating condition assumptions. The eQUEST program is used to develop the basic DOE-2.2 input file. Manual changes are made to the text input file to complete the analysis. A description of the simple box model is shown below:

Table 16 -- DOE-2.2 Base Model Inputs

Model Parameter	**Value**
Shape	Rectangular, 50x40
Conditioned floor area	2000 ft^2
No floors	1
Floor to ceiling	9 ft
Plenum height	3 ft
Window/wall ratio	20%
Window type	CTZ 3,6 – Double low e clear (SHGC =0.42; COG U-Factor = 0.23), CTZ 10,12,14 – Double low e tint (SHGC = 0.37, COG U-value = 0.26)
Exterior wall construction	8 in. concrete tilt-up construction insulated
Exterior wall R-value	CTZ 3,6 R-11 CTZ 10,12,14 – R-13
Infiltration rate	0.3 ACH in occupied zone, varies in attic
Roof construction	Built-up roof over plywood deck
Roof absorptivity and emissivity	Abs = 0.8; emiss = 0.9
Ceiling construction	Acoustic tile
Lighting power density	1.2 W/ft^2
Equipment power density	0.5 W/ft^2
Operating schedule	7 am - 6 pm M-F
No. of people	11
Outdoor air	15 cfm/person
HVAC system	PSZ
Size	6 ton
CFM	2100 cfm
Sensible heat ratio @ ARI conditions	0.7
EER	8.5
Thermostat setpoints	Heating: 70/55; Cooling: 74/85
Fan power	0.375 W/cfm
Supply duct surface area	27% of floor area, per ACM
Duct leakage	36% total leakage; evenly split between supply and return (18% supply, 18% return) for leaky case, 10% total leakage for tight case
Duct insulation R-value	R-4.2, with an air film resistance of 0.7 added to account for external and internal air film resistance
Return leak from outside air	0%
Return system type	Ducted

An eQUEST representation of the building is shown in Figure 7.

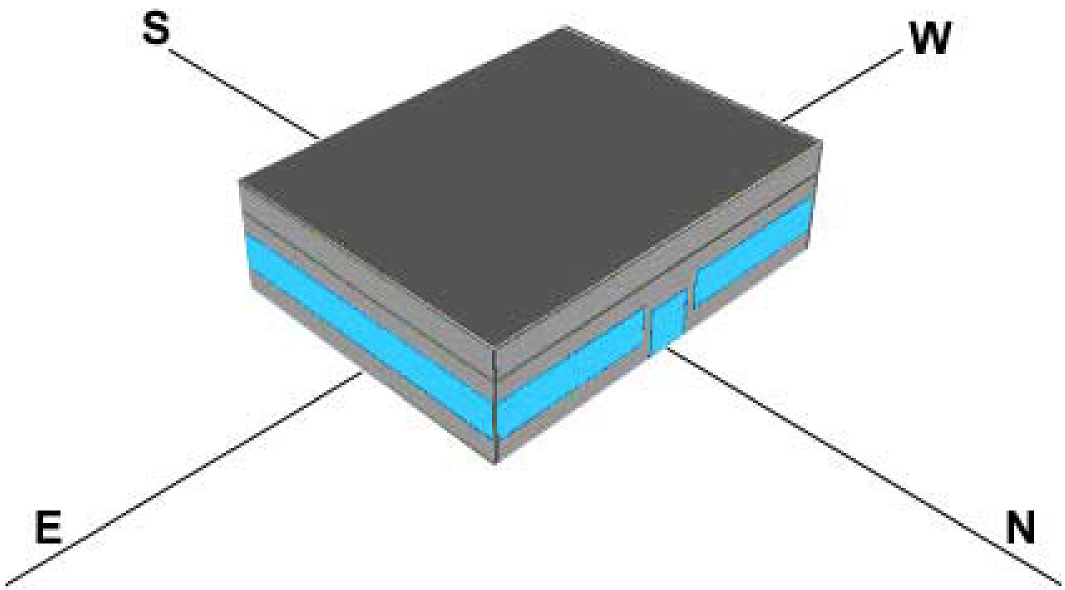

Figure 7 -- eQUEST Illustration of DOE-2 Model Geometry

General Description of Case Studies

The building type considered for this particular study is a single-story office space with an area of 2, 000 ft^2 and a ceiling height of 9 ft, using office occupant densities, internal loads, and schedules. Six climate zones are considered for the roof insulation analysis: CTZ3, CTZ6, CTZ10, CTZ12, and CTZ14.

For the wall construction, the database of the 13 sites surveyed is referenced: 6 were listed as tilt-up, 2 as masonry, 2 as block, and 3 as frame. Also, the wood frame buildings tend to be the older buildings in the sample. As a result, three different conditions of the building are analyzed in this study.

- The first case is a mass building with 8 in. tilt-up concrete as the wall construction and consisting of troffers as light fixtures.
- The second is a mass building with tilt-up concrete but with pendant lighting.
- The third is a frame wall building with pendant lighting.

Each of these three types of conditions are described in the following sections within this report.

Code Requirements for Walls and Roofs

The insulation requirements for walls in the 2001 California Energy Efficiency Standards can be calculated two different ways with dramatically different results. The first method is based upon the R-value of the insulation applied. This method is easy to calculate and easy to enforce. The second method recognizes that the thermal loads in a high-mass building are lower than those in a low-mass building due to thermal storage effects by the mass in the building. Heat loads on both the interior and exterior of the building are absorbed by the building walls and released at night. As a result, medium and high-mass (masonry) buildings have substantially higher U-factor allowances than low-mass (frame wall) buildings.

From discussions with the Tilt-Up Concrete Association and Dave Kelley at Meadow-Burke Engineering, the thickness of single-story, tilt-up walls in California ranges between 6-1/4 and 7-1/4 in., depending upon seismic zone. In seismic zone 3 (much of the Central Valley), the typical thickness is 6-1/4 in., and in seismic zone 4 (Bay Area and LA Basin), the typical thickness is 7-1/4 in. Figure 8 shows a map of the seismic zones in California.[9]

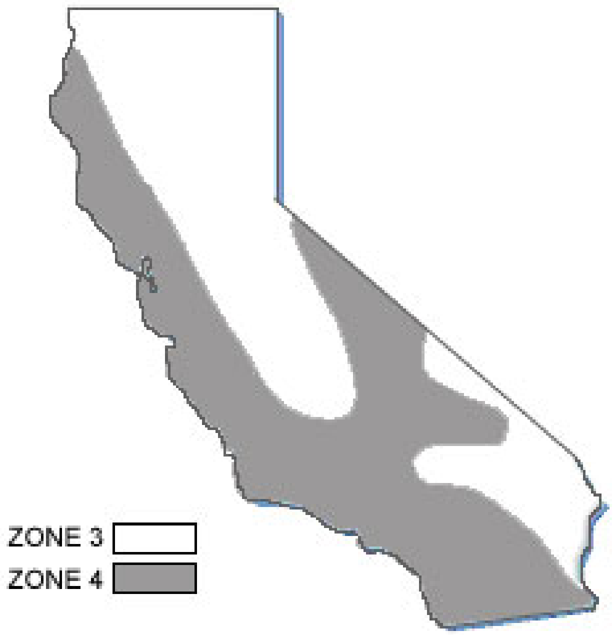

Figure 8 -- Statewide California Seismic Zone Map

Table 17 summarizes the Title 24 wall and roof requirements for the climate zones 3, 6, 10, 12, and 14.[10] In the case of mass walls, the wall U-factor values are used, depending on climate zone. The 7-1/4-in., tilt-up walls modeled in the analysis have a heat capacity (HC) of 16.7 and are therefore considered high mass (an HC greater than15 Btu/ft$^2\cdot$°F). In the case of frame walls, the wall R-values are used, depending on climate zone.

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[9] California Seismic Safety Commission. “The Homeowners Guide to Eathquake Safety,” 1998 Edition. http://www.seismic.ca.gov/pub/CSSC_1997-01_HOG.pdf.

[10] Values are from Table 1-H – Prescriptive Envelope Criteria for Nonresidential Buildings, Section 143 Prescriptive Requirements for Building Envelopes, 2001 California Energy Efficiency Standards.

Table 17 -- California Energy Efficiency Requirements for Opaque Walls and Roofs

	Climate Zones				
Description	1,16	3-5	6-9	2, 10-13	14-15
Wall R-Value	**13**	**11**	**11**	**13**	**13**
Wall U-factor					
Wood frame	0.84	0.092	0.092	0.084	0.084
Metal frame	0.182	0.189	0.189	0.182	0.182
Mass, 7< HC < 15	0.340	*0.430*	*0.430*	*0.430*	*0.430*
Mass, 15 < HC	**0.360**	**0.650**	**0.690**	**0.650**	**0.400**
Roof R-Value	19	19	11	19	19
Roof U-factor	0.057	0.057	0.078	0.057	0.057

If the U-factor method is used, the U-factor requirement for 7-1/4 in. tilt-up walls is equal to or greater than 0.650 [Btu/h·ft^2·°F] for climate zones 2 though 13 for an overall R-value of only 1.54 [h·ft^2·°F/Btu]. In section 141(c)4.A of the Standards, air film resistances are also allowed, which in most cases is 0.17 [h·ft^2·°F/Btu] outside and 0.68 [h·ft^2·°F/Btu] inside so that the thermal resistance without air films of the medium mass wall need only be 0.69 [h·ft^2·°F/Btu]. Given that a nominal 8-in. tilt-up slab (thickness of 7-1/4 in.) has an R-value of 0.80 to 0.48, the slab itself, or the slab in addition to an inch of stucco (R-value of 0.2), will provide the needed thermal resistance without adding insulation.[11]

Architects, insulation contractors, and energy consultants are interviewed via phone to find out whether tilt-up concrete walls are insulated in the conditioned space and in the plenum. The response is that if the wall is furred out to hide electrical wiring and plumbing, then the wall cavity is filled with insulation.

In the case of tilt-up concrete walls when lay-in insulation is used, the plenum walls are not insulated. When the insulation is not placed at the ceiling but at the roof deck, the tilt-up walls on the sides of the plenum may or may not be insulated. This depends on the climate zone, occupancy, and whether the designer realizes that the U-factor method would allow the insulation to be omitted. In order for the building models to reflect general building practice, the plenum walls under insulated roof decks are modeled two ways: with and without plenum wall insulation. For the frame wall case study, the plenum walls are considered to be insulated with insulated roof decks and uninsulated with insulated ceilings.

Plenum Wall Model

The cement tilt-up walls in the DOE-2.2 simulation are modeled as a full 8 in. thick, have an R-value of 0.88, and HC of 18.7. The frame walls are modeled as having an exterior finish of stucco, ½ in. plywood board with insulation installed between the framing members. The walls of the ceiling plenum are not finished, and to maintain appropriate fire rating of the wall assembly, foil faced batt insulation is assumed. R-value of wood frame wall (excluding the insulation) is calculated as 0.83 and HC as 3.18. Both these walls are modeled as layers so that the thermal mass is accurately characterized.

For the models with plenum wall insulation, another layer is added for the thermal resistance of the insulation. The R-value of the insulation applied to the inside surfaces of plenum walls follows the requirements of Title 24 when the R-value method is used to show compliance (shown in Table 17 in the previous section). Thus R-11 insulation is added to the plenum sidewalls in climate zones 3 through 9, and R-13 insulation is added to the plenum sidewalls in the remainder of the climate zones.

The fiberglass batt insulation has a foil-faced vapor barrier to comply with fire safety codes; Kraft paper-faced batts do not meet the flame spread requirements for installations that are not covered by sheet-rock. Foil-faced batts are commonly used in the buildings surveyed. Thus the insulation modeled is foil faced, which has a low surface emittance, and as a result this foil facing increases the interior film R-value from 0.68 (emittance =

[11] p. 22.8 of the 1993 ASHRAE Handbook of Fundamentals thermal resistance values for 144 lb/ft^3 concrete. The 1993 Handbook is referenced here as the 1993 Handbook is referenced in the Standard. Stucco values are from the DOE-2.1A Reference Manual.

90%) to 1.35 (emittance = 20%). See Table 18.[12] The Surface Resistance for Air section of this report goes into more detail on the air film heat transfer coefficients used in the simulation models.

Roofs

Four types of roofing/ceiling combinations are analyzed.

The “under deck” insulated roof is a built-up roof over a plywood deck with foil faced R-11 or R-19 (depending on climate zone) fiberglass batts installed between metal joists under the roof deck. The ceiling is an uninsulated t-bar ceiling with acoustic tiles.

The “above deck” insulated roof has R-11 or R-19 polystyrene insulation sandwiched between the built-up roofing and the plywood deck. The ceiling in this case is an uninsulated t-bar ceiling with acoustic tiles.

The two suspended drywall systems used by the contractors surveyed are the USG system and Chicago-metallic system. The USG system uses 24 gauge t- bars suspended using 12 gauge hanger wires. The drywall is screwed into the t-bars, taped, finished, and then textured. The quotes based on the USG system are used for the cost calculations in this report.

The “lay-in” insulated ceiling has built-up roofing over an uninsulated plywood deck. The acoustic tile t-bar ceiling is insulated with R-11 or R-19 foil faced fiberglass batts. Insulation coverage is parametrically varied to cover between 50-90% of the ceiling surface. These variations in insulation coverage are combined as described in the Lay-In Insulation Coverage Probability Function section.

R-value Calculations

The R-values of each of the building components and the total R-value of the building system are calculated using the 1993 ASHRAE Handbook of Fundamentals.[13] These R-values do not include the inside surface resistance of air. The R-values for roofs have been calculated on the basis of R-19 (CTZ3, CTZ10, CTZ12, CTZ14) and R-11 (CTZ6). As per the 2001 Energy Efficiency Standards, the insulated mass walls and frame walls use the R-value requirements and the uninsulated mass wall case use the U-factor requirements.

[12] Table 1 “Surface Conductances and Resistances for Air,” 1993 ASHRAE Handbook of Fundamentals, p 22.1.

[13] Table 4, "Typical Thermal Properties of Common Building and Insulating materials - Design Values," ASHRAE Handbook of Fundamentals, 1993. pp. 22-6 through 22-9.

Table 18 -- R-Value of Roofs, Walls and Ceilings (Acoustic Tile Ceilings with 50%-90% Insulation Coverage)

Under deck insulated roof		**Above deck insulated roof**	
built-in roof	0.33	built-in roof	0.33
plywood (.75 inch)	0.93	plywood (.75 inch)	0.93
Corrected value of fiber	16.3	Polystyrene (4 inch)	19
Total	17.56	Total	20.26
U factor	**0.057**	**U factor**	**0.049**
Dry wall ceiling- R value		**Acoustic tiles ceiling-90%**	
Mineral fiber	19	Mineral fiber	17.4
Gypboard	0.45	Acoustic tiles	1.25
R values	19.45		
Total	17.64	total	16.91
U factor	**0.06**	**U factor**	**0.06**
Acoustic tiles ceiling-80%		**Acoustic tiles ceiling-70%**	
Mineral fiber	15.8	Mineral fiber	14.2
Acoustic tiles	1.25	Acoustic tiles	1.25
total	13.89	total	11.19
U factor	**0.072**	**U factor**	**0.09**
Acoustic tiles ceiling-60%		**Acoustic tiles ceiling-50%**	
Mineral fiber	12.6	Mineral fiber	11
Acoustic tiles	1.25	Acoustic tiles	1.25
total	8.81	total	6.75
U factor	**0.114**	U factor	0.15
Mass Wall-insulated		**Mass wall-Uninsulated**	
8" heavy wt concrete (density 140 lb)	0.616	8" heavy wt concrete (density 140 lb)	0.62
fiber glass batt	11	stucco	0.20
stucco	0.2		
R value	11.82		
Total	10.92	Total	0.82
U factor	**0.094**	U factor	1.23
Frame wall-insulated		**Frame wall-uninsulated**	
1/2 in plywood	0.63	1/2 in plywood	0.63
fiber glass batt	11		
stucco	0.2	stucco	0.2
R value	11.83	R value	0.83
Total	11.15	Total	1.25
U factor	**0.090**	**U factor**	**0.801**

Heat Capacity Calculations

The heat capacities for the roof systems and the wall systems are calculated using the specific heat, density, and thickness of the building materials. The heat capacity, in units of Btu/ft^2·°F is calculated from properties of building materials by the following equation:

$$HC = Cp \times \rho \times L$$

where,

Cp = specific heat, $Btu/lb_m \cdot °F$

ρ = density, lb_m/ft^3

L = thickness of materials, ft

Table 19 -- Heat Capacities of Building Materials

Material	Specific Heat	Density	Thickness (ft)	Heat Capacity
Tit-up slab, 8" thick heavy weight concrete	0.2	140	0.604	16.92
Roof deck, 1" plywood	.29	34	.06	.62
R-19 Rigid insulation	.2	6	.29	.35
Acoustic tiles	.32	18	.04	.36
Drywall (gyp board)	.2	50	.04	.42
Stucco	.2	166	.08	2.77
½" plywood for frame wall	.29	34	.041	.41

According to the 2001 Energy Efficiency Standards, the U-Factor of the wall is dependent on the heat capacity of the wall for various climate zones.

Surface Resistance for Air

The surface resistance for air for both the plenum wall and the roof is listed in Table 20. This is not included in the calculation for R-value of the various building component layers. The surface resistance of air changes with the surface orientation (wall or roof), emissivity of surface (reflective/non-reflective), and direction of heat flow (2001 ASHRAE fundamentals).

Table 20 -- Surface Resistance of Air for Roofs, Ceilings, and Walls

Description	Surface orientation	Direction-heat flo	Surface	Emittance	R-value
plenum wall	vertical	horizontal	reflective	0.2	1.35
plenum wall	vertical	horizontal	non-reflectiv	0.9	0.68
insulated roof - metal joist	horizontal	downward	reflective	0.2	2.7
lay-in insul	horizontal	downward	reflective	0.2	2.7
ceiling(without insulation)	horizontal	downward	non-reflectiv	0.9	0.92
insulated roof rigid	horizontal	downward	non-reflectiv	0.9	0.92

Ceiling Combined Conductance and Infiltration R-values

As described in the section on Ceiling Air Leakage, air infiltration or exfiltration is a key component of heat transfer through the ceiling plane for ceiling tiles installed on a T-bar ceiling. Air exfiltration across the ceiling plane is modeled as a two-zone pressure system with the driving force being generated by the HVAC system pressuring the conditioned space. A graphic representation of this model is shown in Figure 9.

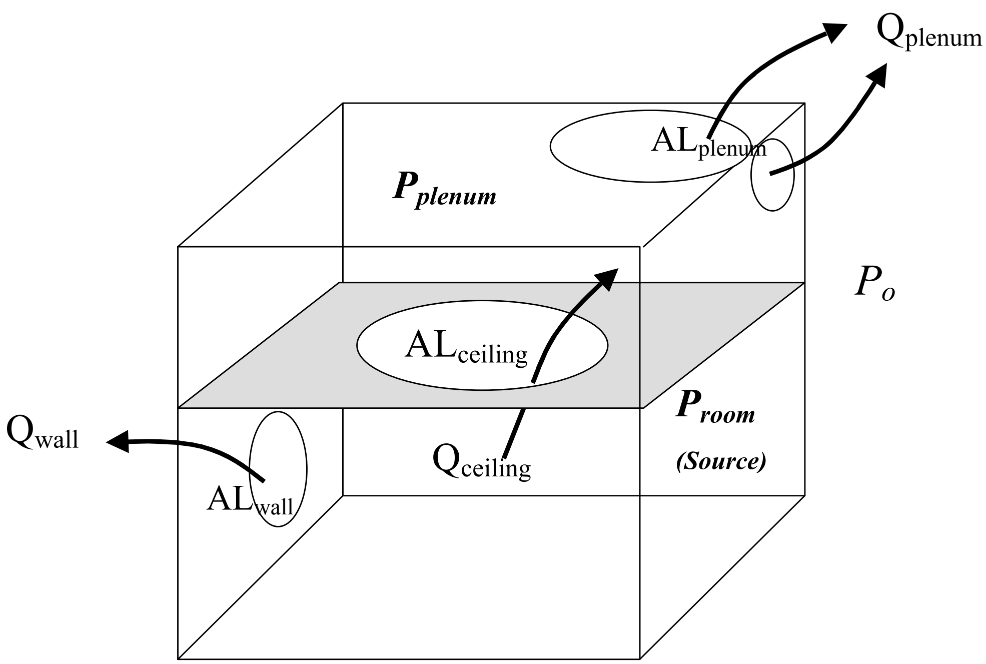

Figure 9 -- Pressure Model to Evaluate Ceiling Infiltration

This model assumes that HVAC-induced pressures in the conditioned space act as a source and that the entire building is placed in a regime where the building is exfiltrating across all envelope surfaces. This assumption is reasonable for the summer, when wind speeds are low and stack effect forces are low. In such a regime, Q_{plenum}, the flow of air exfiltrating from the walls and the roof of the plenum, is equal to $Q_{ceiling}$, the flow of air passing from the conditioned space to the plenum through leaks in the ceiling. Given this conservation of mass of air, the following relation for volumetric flow rates of air (cubic feet per second) can be derived using a form of Bernoulli's equation.

$$Q_{plenum} = AL_{plenum}\sqrt{\frac{2\,(P_{plenum} - P_o)\,g_c}{\rho_{air}}} = Q_{ceiling} = AL_{ceiling}\sqrt{\frac{2\,(P_{room} - P_{plenum})\,g_c}{\rho_{air}}}$$

where,

AL_{plenum}	=	leakage area of the plenum walls and roof, ft^2
P_{plenum}	=	pressure of the plenum, lb_f/ft^2
Po	=	outdoor air pressure, lbf/ft^2
g_c	=	conversion constant, 32.17 lb_m/slug
ρ_{air}	=	density of air, .lb_m/ft^2
$AL_{ceiling}$	=	leakage area of the ceiling, ft^2
P_{room}	=	pressure of the room, lb_f/ft^2

If the pressures are described in terms of gauge pressure relative to the outside pressure, Po is zero. If both sides of the equation are squared and rearranged, the pressure in the plenum, P_{plenum}, can be calculated relative to the pressure in the room, P_{room}, and the relative areas of leaks in the envelope.

$(AL_{plenum})^2\,(P_{plenum}) = (AL_{ceiling})^2\,(P_{room} - P_{plenum})$

Rearranging the terms results in:

$[AL_{plenum}{}^2 + AL_{ceiling}{}^2]\,(P_{plenum}) = (AL_{ceiling})^2\,(P_{room})$

$$P_{plenum} = P_{room} \frac{AL_{ceiling}^2}{AL_{plenum}^2 + AL_{ceiling}^2}$$

Solving for flows through the roof or across the ceiling by substituting P_{plenum}.

$$Q_{plenum} = AL_{plenum} \sqrt{\frac{2\ P_{room} \frac{AL_{ceiling}^2}{AL_{plenum}^2 + AL_{ceiling}^2}\ g_c}{\rho_{air}}}$$

or

$$Q_{ceiling} = AL_{ceiling} \sqrt{\frac{2\ (P_{room} - P_{room} \frac{AL_{ceiling}^2}{AL_{plenum}^2 + AL_{ceiling}^2})\ g_c}{\rho_{air}}}$$

These equations are used to develop a two-zone model of the 2,000-ft^2 prototype building used for the simulations. This building is of tilt-up construction with a 20% window-to-wall ratio, with a 9 ft high ceiling and a 3 ft tall plenum above the ceiling. The leakage areas for each major component in this model are specified in Table 21. Except for the FSEC values for the acoustic t-bar ceiling, all of the values come from the ASHRAE Handbook of Fundamentals.

The leakage areas in the tilt-up slab walls include a vertical joint ever 8 ft for connecting the wall sections together. The drywall ceiling is modeled as having five recessed cans or other similar penetrations. When modeling a ventilated roof, the assumption is that the roof has 1/150th of the roof area in vent openings as required by the UBC when ventilation is required. The unventilated or “tight” roof is based on raised floor leakage areas with the addition of 10 electrical or plumbing penetrations and a joint where the wall meets the roof deck. Raised floor leakage areas are used because of similar construction practices of building a continuous floor and a flat roof, and the lack of other data sources. There is also a small amount of leakage area for the plenum sidewalls.

Table 21 -- Component Leakage Areas for 2,000-ft^2 Prototype Building

		Efective leakage area		
Building component	**SF**	**in2/ft2**	**SF**	**Comments**
Total door width	105	0.23	0.168	Door, masonry not caulked
Total window width	324	0.053	0.119	Sealed window
Sill joint	180	0.2	0.25	per lin ft
Wall	1191	0.02	0.213	Precast panel
Total wall			0.75	
Ceiling	2000	0.3	4.193	Acoustic tile
Drywall w/5 cans	2000	0.01	0.181	Drywall
Roof 1/150th free area	2000	0.96	13.33	Ventilated roof per UBC
Tight roof	2000	0.04	0.567	Roof, wall joint, 10 penetrations
Plenum side wall	540	0.02	0.097	Precast panel

The building models created out of the equations described above result in the component leakages shown in Table 21. The pressure in the conditioned space, P_{room}, is varied until room air exchange rate for the building with a ventilated attic and a drywall ceiling is around 0.4 air changes per hour. This trial and error process yields a conditioned space gauge (relative to outside air) pressure of 0.0052 psf (025 Pascals). This same conditioned space pressure is applied to all of the other building configurations. The results of this analysis are given in Table 22.

Table 22 -- Flows and Effective U-factors from Two-Zone Flow Analysis

Roof	Ceiling	psf Proom	psf Pplenum	ft3/s Qplenum	ft3/s Qceiling	ft3/s Qwall	ft3/s QrmTotal	Qroom ACH Total	U ceiling	Ceil CFM
Ventilated	Drywall	0.0052	9.39E-07	0.383	0.383	1.591	1.97	0.39	0.0124	23.0
Ventilated	T-bar	0.0052	4.62E-04	8.492	8.492	1.591	10.08	2.02	0.2751	509.5
Unventilated	Drywall	0.0052	4.58E-03	0.132	0.132	1.591	1.72	0.34	0.0043	7.9
Unventilated	T-bar	0.0052	5.20E-03	0.141	0.141	1.591	1.73	0.35	0.0046	8.5

Several conclusions can be drawn from the results in this table:

- Given the low leakage rates through an unventilated roof, it doesn't matter how much leakage area exists in the ceiling, the pressure in the plenum stays close to that in the conditioned space and thus the flow of air is relatively low. The model assumes that duct leaks are balanced (i.e., the leakage by supply ducts equals that of return ducts). Even if this assumption is violated, most of the air in the plenum is not lost to the outside and this air is inside of the thermal envelope.
- A shown in the second row of data in Table 22, the combination of a ventilated ceiling and a t-bar ceiling results in high exfiltration rates. As compared to the drywall ceiling (first row), air leakage through the t-bar ceiling increases the flows into the ceiling by a factor of 200.
- The t-bar ceiling in the second row of the table has a ceiling leakage rate of 8 cubic feet per second. This drives the overall leakage of the room so that the room loses 10 cubic feet per second. For the 9 ft tall room in the 2,000-ft^2 building (volume = 18,000 cubic feet) this is equivalent to 2 air changes per hour as shown below:

$$ACH = \frac{10.08\ \mathrm{ft}^3/\mathrm{sec} \times 3{,}600\ \mathrm{sec/hr}}{18{,}000\ \mathrm{ft}^3} = 2.02\ \text{air changes per hour}$$

- However, even at the high leakage rate of the t-bar ceiling, this is only 28% of the 1,722 cfm supply airflow.
- The tenth column in Table 22 gives the infiltration U-factor in units of Btu/h·ft^2·°F across each ceiling.

The infiltration U-factor in units of Btu/h·ft^2·°F is calculated by the relation:

U_{infil} = $(\mathrm{cfm/ft}^2)(\rho_{air})(C_p)(\mathrm{min/hr})$

Where,

Cfm/ft^2 = the infiltration rate in cfm per ft^2 of ceiling area

ρ_{air} = density of air, 0.075 lb$_m$/ft^3

C_p = specific heat of air, 0.24 Btu/lb$_m$·°F

min/hr = conversion, 60 minutes per hour

As an example, the drywall ceiling (first row of Table 22) in conjunction with a ventilated attic has a flow rate of 23 cfm for the 2,000 ft^2 building, or 23/2,000 = 0.0115 cfm/ft^2. The resulting infiltration U-factor is:

U_{infil} = (0.0115)(0.075)(0.24)(60) = 0.0124 Btu/h·ft^2·°F

These U-factors are applied in parallel with the U-factor of the ceiling and its air films.

Total Ceiling U-Factors

The total ceiling U-factor is calculated based on the U-factor of the ceiling with infiltration. The upper and lower air film U-factor is calculated based on the percentage of insulation coverage and the R-value of the air coefficients. When the ceilings are insulated (assuming foil faced batts), the top face of the ceiling has a relatively high air film thermal resistance due to the low emittance of the foil. When ceilings are uninsulated, the air film thermal resistance is lower due to the higher emittance of the ceiling tile (assumed to be 0.9). The overall U-factor of the ceiling, including infiltration, is then calculated by adding the U-factors of the percentage of insulation, the acoustic tiles, the surface air coefficients, and the infiltration U-factor (see previous section).

Infiltration across the t-bar ceilings based on the FSEC research is used to determine the U-factor impact due to infiltration.

Table 23 -- U-Factors and R-Values of Ventilated and Unventilated Ceilings With and Without Infiltration

Description	Roof	Overall-Ufactor	Infiltration U	U-factor w/ infil	R-factor with infil
Uninsulated Ceiling	Unventilated	0.324	0.005	0.328	3.05
Drywall	Ventilated	0.043	0.012	0.056	17.94
Insulated Ceiling-90%	Unventilated	0.046	0.005	0.051	19.61
Insulated Ceiling-80%	Unventilated	0.052	0.005	0.056	17.76
Insulated Ceiling-70%	Unventilated	0.058	0.005	0.063	15.93
Insulated Ceiling-60%	Unventilated	0.066	0.005	0.071	14.12
Insulated Ceiling-50%	Unventilated	0.077	0.005	0.081	12.31
Drywall	Unventilated	0.043	0.004	0.048	20.99
Insulated Ceiling-90%	Ventilated	0.046	0.275	0.322	3.11
Insulated Ceiling-80%	Ventilated	0.052	0.275	0.327	3.06
Insulated Ceiling-70%	Ventilated	0.058	0.275	0.333	3.00
Insulated Ceiling-60%	Ventilated	0.066	0.275	0.341	2.93
Insulated Ceiling-50%	Ventilated	0.077	0.275	0.352	2.84

Lay-In Insulation Coverage Probability Function

Site survey data collected on the fraction of ceiling coverage indicates that most buildings have between 50% and 90% insulation coverage. Since the effect of insulation coverage is likely non-linear, simulating average insulation coverage would not give an accurate estimate of energy consumption from the class of buildings containing lay-in insulation.

The energy estimating method used in this project simulates the energy consumption of buildings at different levels of lay-in insulation coverage. Weighting the energy consumption of each level of insulation coverage by the probability of that insulation coverage creates a weighted average energy consumption for buildings with lay-in insulation.

Sorting the on-site observations into bins of insulation-coverage fractions of 10% increments creates estimates of insulation coverage probabilities. This sorted data is shown in the histogram in Figure 10.

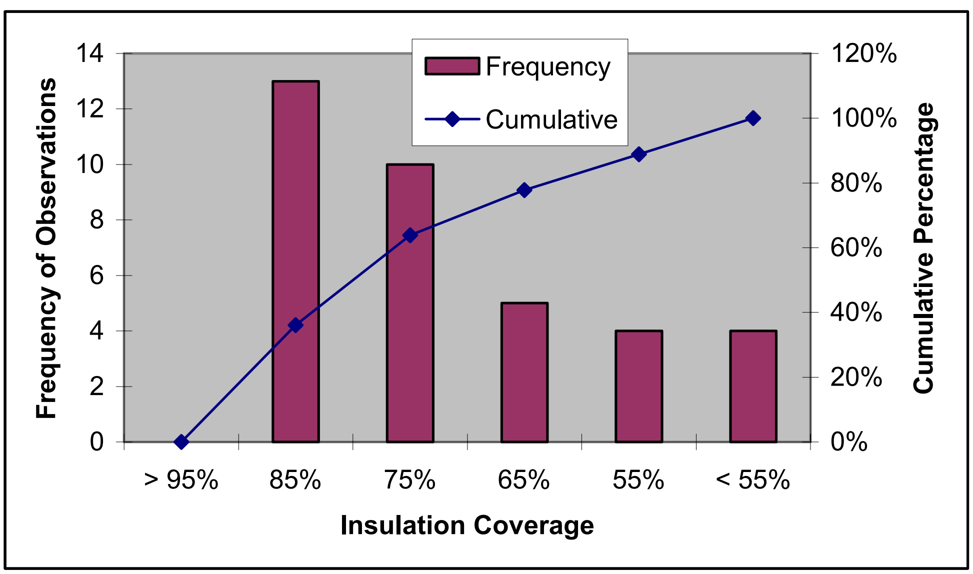

Figure 10 -- Insulation Coverage Frequency Histogram

Table 24 contains the ranges of insulation coverage in each bin, the associated insulation fraction used in the model to represent this range of coverage, and the probability that insulation coverage falls in a given bin. The modeled insulation fraction is the midpoint value for the bin.

Table 24 -- Modeled Insulation Fraction and Probability of Insulation Coverage in 10% Bins

Range of Insulation Coverage	Modeled Insulation	Probability Weighting
> 95%	N/A	0%
95% to 85%	90%	36%
85% to 75%	80%	28%
75% to 65%	70%	14%
65% to 55%	60%	11%
< 55%	50%	11%

Mass Building With Troffers

Building Description

This building study consists of an 8-in. thick, tilt-up concrete wall. The building is a single-story office space with an area of 2,000 ft^2, using office occupant densities, internal loads, and schedules. Six climate zones were considered for the roof insulation analysis: CTZ3, CTZ6, CTZ10, CTZ12, and CTZ14.

Heat Transfer of Lighting Heat

The fraction of lighting heat to the plenum wall versus the conditioned space is considered to be 30% for all the roof conditions, except the "drywall ceiling type" where the assumed fraction is 10%. The section on Heat Loss From Luminaires describes the source of the data used for this parameter. The lighting power density used in the simulation is 1.2 W/ft^2, which is the prescriptive maximum for offices, and is below the 1.9 W/ft^2 allowed in retail spaces.

Parameters

1. The building parametric runs have 10 different types of roofing insulation conditions in conjunction with an unventilated plenum. These parametric runs are:

- "Under deck" insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.
- "Under deck" insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- "Above deck" insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.
- "Above deck" insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- "Drywall" uninsulated roof deck and **uninsulated** plenum walls with an insulated drywall (low infiltration leakage area) ceiling.
- "90% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **90%** of the t-bar ceiling area insulated.
- "80% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **80%** of the t-bar ceiling area insulated.
- "70% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **70%** of the t-bar ceiling area insulated.
- "60% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **60%** of the t-bar ceiling area insulated.

- “50% lay-in” uninsulated roof deck and **uninsulated** plenum walls with **50%** of the t-bar ceiling area insulated.

2. The building parametric runs have six different types of roofing insulation conditions in conjunction with a ventilated plenum. Note the insulated roof deck cases are not included in this set of parametrics. If the thermal boundary is at the roof level, ventilating the plenum would violate the infiltration integrity of the conditioned space. The parametrics with a ventilated plenum are:

- Drywall” uninsulated roof deck and **uninsulated** plenum walls with an insulated drywall (low infiltration leakage area) ceiling.
- “90% lay-in” uninsulated roof deck and **uninsulated** plenum walls with **90%** of the t-bar ceiling area insulated. Air leakage through the ceiling uses the FSEC values.
- “80% lay-in” uninsulated roof deck and **uninsulated** plenum walls with **80%** of the t-bar ceiling area insulated. Air leakage through the ceiling uses the FSEC values.
- “70% lay-in” uninsulated roof deck and **uninsulated** plenum walls with **70%** of the t-bar ceiling area insulated. Air leakage through the ceiling uses the FSEC values.
- “60% lay-in” uninsulated roof deck and **uninsulated** plenum walls with **60%** of the t-bar ceiling area insulated. Air leakage through the ceiling uses the FSEC values.
- “50% lay-in” uninsulated roof deck and **uninsulated** plenum walls with **50%** of the t-bar ceiling area insulated. Air leakage through the ceiling uses the FSEC values.

In order to study the effect of duct leakage on the effectiveness of lay-in insulation and vice versa, all of the above insulation parameters are evaluated with a low leakage (8% leaks – 4% supply and 4% return leaks) duct system and with high leakage (36%) ducts.

Based on the on-site survey observations, two types of duct insulations are used in the models R 4.2 and R 8.

The effect of five different plenum heights is also analyzed. The plenum heights included in the study are 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft.

Results

Cooling and Heating Loads

The total cooling and heating loads (KBtu/ft^2) are plotted for the various insulation conditions and climate zones that are simulated using the DOE-2 model. The total TDV (for a 30 year period) and TDV savings are also plotted. The graphs of all the results for climate zone 3 are shown in Appendix A.

Measure Costs

Interviews with contractors are conducted to get the latest pricing information for the types of insulations and ceilings considered in the study. As a reference, the *RS Means Building Construction Cost Data, 15th Annual Edition, 2002 Western Edition*, is used as an industry standard against which to compare pricing information.

The lookup tables in the Means Catalogue provide an average cost for any particular item. To make a sound comparison with the cost data obtained from the contractors, the data obtained from the lookup tables is adjusted using city cost indexes. Averages for the cities of Sacramento, Stockton, and Vallejo are used to get an average city index, which is multiplied by the values from the lookup tables.

The cost estimates shown here are the average of the RS Means catalog prices and the average costs from the phone surveys (at least three quotes per building component).

The costs presented for each survey includes the cost of materials, labor, and the contractors’ overheads and profits. The interviewees are asked to give a percent value of labor in the cost they report. Some of the contractors refuse to give out this information for competitive reasons, and hence are not reported. Detailed cost estimates are provided in Appendix D.

Table 25 -- Cost Estimates ($) of Insulation on Roof Decks and Ceilings for Climate Zones 3, 6, 10, 12, 14 Based on Plenum Heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft

CZ 03

	Lay-in insulation on Acoustic Tiles	*Lay-in insulation on Drywall ceiling*	*Uninsulated plenum walls, non-rigid insulation under metal deck*	*Uninsulated plenum walls, rigid insulation above metal deck*	*Insulated plenum walls (conc), non-rigid insulation under metal deck*	*Insulated plenum walls (conc), rigid insulation above metal deck*	*Insulated plenum walls (framed), non-rigid insulation under metal deck*	*Insulated plenum walls (framed), rigid insulation above metal deck*
Plenum 3'	$5,050	$7,895	$5,639	$7,091	$6,053	$7,505	$5,943	$7,396
Plenum 6'	$5,050	$7,895	$5,639	$7,091	$6,467	$7,919	$6,248	$7,700
Plenum 9'	$5,050	$7,895	$5,639	$7,091	$6,881	$8,333	$6,553	$8,005
Plenum 12'	$5,050	$7,895	$5,639	$7,091	$7,295	$8,747	$6,857	$8,310
Plenum 15'	$5,050	$7,895	$5,639	$7,091	$7,709	$9,161	$7,162	$8,614

CZ 06

	Lay-in insulation on Acoustic Tiles	*Lay-in insulation on Drywall ceiling*	*Uninsulated plenum walls, non-rigid insulation under metal deck*	*Uninsulated plenum walls, rigid insulation above metal deck*	*Insulated plenum walls, non-rigid insulation under metal deck*	*Insulated plenum walls, rigid insulation above metal deck*	*Insulated plenum walls (framed), non-rigid insulation under metal deck*	*Insulated plenum walls (framed), rigid insulation above metal deck*
Plenum 3'	$4,796	$7,641	$5,425	$5,970	$5,839	$6,384	$5,730	$6,275
Plenum 6'	$4,796	$7,641	$5,425	$5,970	$6,253	$6,798	$6,035	$6,579
Plenum 9'	$4,796	$7,641	$5,425	$5,970	$6,667	$7,212	$6,339	$6,884
Plenum 12'	$4,796	$7,641	$5,425	$5,970	$7,081	$8,040	$6,644	$7,189
Plenum 15'	$4,796	$7,641	$5,425	$5,970	$7,495	$8,040	$6,949	$7,493

CZ 10, 12, 14

	Lay-in insulation on Acoustic Tiles	*Lay-in insulation on Drywall ceiling*	*Uninsulated plenum walls, non-rigid insulation under metal deck*	*Uninsulated plenum walls, rigid insulation above metal deck*	*Insulated plenum walls, non-rigid insulation under metal deck*	*Insulated plenum walls, rigid insulation above metal deck*	*Insulated plenum walls (framed), non-rigid insulation under metal deck*	*Insulated plenum walls (framed), rigid insulation above metal deck*
Plenum 3'	$5,050	$7,895	$5,639	$7,091	$6,094	$7,546	$5,967	$7,420
Plenum 6'	$5,050	$7,895	$5,639	$7,091	$6,549	$8,002	$6,296	$7,748
Plenum 9'	$5,050	$7,895	$5,639	$7,091	$7,005	$8,457	$6,625	$8,077
Plenum 12'	$5,050	$7,895	$5,639	$7,091	$7,460	$8,913	$6,953	$8,406
Plenum 15'	$5,050	$7,895	$5,639	$7,091	$7,916	$9,368	$7,282	$8,734

Benefit Cost Ratio

The benefit cost analysis is done based on the TDV savings and the difference in the material costs of all the roofing insulation options as compared to lay-in insulation costs. The following tables show the benefit cost ratios for climate zone 3, along with a summary of benefit cost ratios of all the five climate zones under study. The benefit cost ratios for climate zones 6, 10, 12, and 14 are in Appendix A. The naming convention used in all the following benefit cost ratio tables is described in Table 26.

Table 26 -- Description of Naming Convention Used in the Benefit Cost Ratio Tables

Name	Description
Under deck-plenum-insu.	Under deck insulated roof with insulated plenum walls and an uninsulated t-bar ceiling
Above deck-plenum-insu.	Above deck insulated roof with insulated plenum walls and an uninsulated t-bar ceiling
Under deck-plenum-uninsul.	Under deck insulated roof with uninsulated plenum walls and an uninsulated t-bar ceiling
Above deck-plenum- uninsul.	Above deck insulated roof with uninsulated plenum walls and an uninsulated t-bar ceiling
Drywall ceiling -UV	Uninsulated roof deck and uninsulated plenum walls with an insulated drywall (low infiltration leakage area) ceiling-Unventilated
Drywall ceiling -V	Uninsulated roof deck and uninsulated plenum walls with an insulated drywall (low infiltration leakage area) ceiling-Ventilated
Lay-in -UV	Uninsulated roof deck and uninsulated plenum walls with average value of 50%-90% of the t-bar ceiling area insulated with unventilated plenum
Lay-in -V	Uninsulated roof deck and uninsulated plenum walls with average value of 50%-90% of the t-bar ceiling area insulated with ventilated plenum

1. *Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall, and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3 ft, 6 ft, 9 ft, 12 ft and 15 ft.*

Table 27 shows the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof deck, drywall, and lay-in ceiling conditions for climate zone 3. The benefit cost ratios are calculated for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft and 15 ft. The calculations are based on the difference between the total TDV costs of all insulation conditions with leaky ducts to all insulation conditions with tight ducts. This value was then divided by the cost of adding insulation and sealing the ducts.

The results reveal that tightening the ducts shows a higher cost effectiveness for both the drywall (maximum for a ventilated drywall) and the lay-in insulated ceiling as compared to the insulated roof decks. In the case of insulated roof decks, the ones with insulated plenum wall are not cost effective for climate zone 3. The benefit cost ratio increases with the increase in the plenum heights.

Table 27 -- Benefit Cost Ratio of Tightening and Adding Insulation to Ducts for Insulated Roofs, Drywall and Lay-In Ceiling from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3 ft, 6 ft, 9 ft, 12 ft and 15 ft- Climate Zone 3

CTZ3
Benefit cost for Tightening Ducts for all insulation conditions

	Insulated Plenum Wall		Uninsulated Plenum Wall					
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling- V	Lay-in- UV	Lay-in-V
3	0.66	0.61	0.89	0.81	3.33	3.61	3.24	2.79
6	0.71	0.66	1.09	0.98	3.13	3.39	3.09	2.84
9	0.75	0.70	1.23	1.12	2.95	3.24	2.96	2.88
12	0.79	0.75	1.35	1.23	2.81	3.11	2.84	2.90
15	0.83	0.79	1.44	1.33	2.69	3.00	2.73	2.92

Table 28 shows the summary of benefit cost ratios for tightening ducts for climate zones 3, 6, 10, 12, and 14 based on which plenum heights show cost effectiveness. In Table 28, “None” represents no benefit costs for any of the plenum heights; “All” represents cost effectiveness for all plenum heights; “>3’”, “>6’” and “>9’” represents cost effectiveness above 3 ft, 6 ft, and 9 ft of plenum height. The drywall ceiling and lay-in ceiling, both show cost effectiveness in tightening the ducts for all plenum heights and for all climate zones. The roof decks with insulated and uninsulated plenum walls show cost effectiveness for all plenum heights for climate zone 14.

Table 28 -- Summary of Cost Effectiveness of Tightening Ducts for Insulated Roofs, and Drywall and Lay-In Ceilings for Climate Zones 3, 6, 10, 12, and 14 Based on Which Plenum Heights Show Cost Effectiveness

Summary-Cost effectiveness of tightening ducts

Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V	Lay-in-UV	Lay-in-V
CTZ3	None	None	>3'	>6'	All	All	All	All
CTZ6	>3'	>6'	All	All	All	All	All	All
CTZ10	All	>3'	All	All	All	All	All	All
CTZ12	>6'	>9'	All	All	All	All	All	All
CTZ14	All	All	All	All	All	All	All	All

2. Benefit cost ratio of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceiling with tight ducts (R 8)-Climate zone 3 for plenum heights of 3 ft, 6 ft, 9 ft, 12 ft and 15 ft.

The second case determines the benefit cost ratios for insulated roof deck conditions with leaky ducts (with R4.2 duct insulation) versus insulated lay-in ceilings with tight ducts (with R 8 duct insulation). This benefit cost ratio is calculated for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft. This benefit cost ratio is calculated by taking the difference between the total TDV cost of lay-in insulation compared to the total TDV cost of the roof insulation. This is then divided by the difference between the cost of insulation for roof decks with leaky ducts and the cost of insulation for a lay-in ceiling with tight ducts.

Table 29 shows that for climate zone 3 with uninsulated plenum walls, under deck insulation shows high cost effectiveness for all plenum heights. In the case of the above deck insulated roof with uninsulated plenum walls, the benefit cost ratio is higher than one for plenum heights of 3 ft and 6 ft. In the case of roof decks with insulated plenum walls, the above deck insulated roof shows no cost effectiveness for all plenum heights. The under deck insulated roof with insulated plenum was cost effective for plenum heights of 3 ft and 6 ft.

Table 29 -- Benefit Cost Ratios of Insulated Roofs with Leaky Ducts (R4.2) Versus Insulated Lay-In Ceilings with Tight Ducts (R 8) for Plenum Heights 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft -Climate Zone 3

CTZ3 Benefit costs of Leaky roofs versus Tight layin ceilings				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	3.31	**0.77**	Infinite *	1.39
6	1.03	**0.41**	Infinite *	1.18
9	**0.41**	**0.22**	Infinite *	**0.99**
12	**0.16**	**0.11**	Infinite *	**0.83**
15	**0.03**	**0.04**	Infinite *	**0.69**

(Note: infinite* indicates immediate cost benefit)

Table 30 shows a summary of cost effectiveness of insulated roof decks versus insulated lay-in ceilings for climate zones 3, 6, 10, 12, and 14 based on which plenum heights show cost effectiveness. In the table below, “None” represents no benefit costs for any of the plenum heights (3 ft, 6 ft, 9 ft, 12 ft, and 15ft); “All” represents cost effectiveness for all plenum heights, “<6’”, “<9’”, “<12’” and “<15’” represents cost effectiveness below 6 ft, 9 ft, 12 ft, and 15 ft of plenum height. Here, the under deck insulated roof with uninsulated plenum walls shows cost effectiveness for all plenum heights and for all climate zones. Under deck insulated roofs with insulated plenum walls shows cost effectiveness for all plenum heights for climate zones 14 and for all heights less than 15 ft for climate zones 10 and 12.

Table 30 -- Summary of Cost Effectiveness of Insulated Roofs with Leaky Ducts Versus Insulated Lay-In Ceilings with Tight Ducts for Climate Zones 3, 6, 10, 12, and 14 Based on Which Plenum Heights Show a Cost Effectiveness

Summary-Cost effectiveness of leaky roofs vs tight lay-in ceiling				
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
CTZ3	<6'	none	All	<6'
CTZ6	3'	3'	All	<12'
CTZ10	<15'	<9'	All	<12'
CTZ12	<15'	<9'	All	<12'
CTZ14	All	<12'	All	<12'

3. *Benefit cost ratios for insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).*

Table 31 shows the benefit cost ratios for climate zone 3 of insulated roof decks and drywall ceilings with tight ducts (including R 8 duct insulation) versus insulated lay-in ceilings with tight ducts for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft. This benefit cost ratio is calculated by taking the difference between the total TDV cost of lay-in insulation with the total TDV cost of roof deck and drywall ceiling insulation. This is then divided by the difference between the cost of insulation for roof decks and drywall ceilings with tight ducts and the cost of insulation for lay-in ceilings with tight ducts.

The results show that the under deck insulated roof with uninsulated plenum wall shows cost effectiveness for all plenum heights while the above deck insulated roof with uninsulated plenum wall shows cost effectiveness for plenum heights below 12 ft. In the case of insulated plenum wall conditions, the under deck insulated roof shows cost effectiveness for a plenum height of 3 ft, while the above deck insulated roof shows no cost effectiveness. The drywall ceiling (unventilated and ventilated) does not show cost effectiveness for any plenum heights.

Table 31 -- Benefit Cost Ratios of Insulated Roofs and Drywall Ceilings with Tight Ducts (R 8) Versus Insulated Lay-In Ceilings with Tight Ducts (R 8) for Plenum Heights of 3 ft, 6 ft, 9 ft, 12 ft and 15 ft -Climate Zone 3

CTZ3 Benefit cost Ratio- Tight Ducts (R 8)						
	Insulated Plenum Wall		***Uninsulated Plenum Wall***			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling- V
3	1.72	**0.73**	4.07	1.22	**0.33**	**0.49**
6	**0.89**	**0.46**	3.76	1.12	**0.28**	**0.38**
9	**0.52**	**0.31**	3.45	1.03	**0.22**	**0.29**
12	**0.33**	**0.21**	3.18	**0.95**	**0.18**	**0.23**
15	**0.21**	**0.15**	2.94	**0.88**	**0.14**	**0.18**

Table 32 shows a summary of cost effectiveness of insulated roof decks and drywall ceilings with tight ducts versus insulated lay-in ceilings with tight ducts for climate zones 3, 6, 10, 12, and 14 based on which plenum heights show cost effectiveness. In the table below, “None” represents no cost effectiveness for any of the plenum heights (3 ft, 6 ft, 9 ft, 12 ft, and 15 ft); “All” represents cost effectiveness for all plenum heights; “<6’”, “<9’”, “<12’”, and “<15’” represents cost effectiveness below 6 ft, 9 ft, 12 ft, and 15 ft of plenum height. The results indicate that the under deck insulated roof with uninsulated plenums are cost effective for all plenum heights and for all climate zones. The ventilated plenum drywall case shows cost effectiveness for all plenum heights in climate zone 14, and for a height of 3 ft for climate zones 12 and 10.

Table 32 -- Summary of Cost Effectiveness of Insulated Roofs and Drywall Ceilings with Tight Ducts Versus Insulated Lay-In Ceilings with Tight Ducts for Climate Zones 3, 6, 10, 1,2 and 14 Based on Which Plenum Heights Show Cost Effectiveness

Summary-Cost effectiveness of tight roofs/drwall ceiling vs tight lay-in ceiling						
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
CTZ3	3'	None	All	<12'	None	None
CTZ6	3'	None	All	All	None	None
CTZ10	<15'	<12'	All	All	None	3'
CTZ12	<15'	<9'	All	All	None	3'
CTZ14	All	<12'	All	All	<12'	All

Mass Building with Pendant Lighting

Description of Building Parametrics

Another set of DOE-2 simulations are carried out with slight modifications to the existing building model described above. Here, the building wall construction is considered to have tilt-up concrete, but the troffers are replaced with pendant lighting. In this new set of simulation runs, only the ventilated lay-in insulations are considered for analysis and the rest of the unventilated ceiling conditions are removed from the model. Two types of duct conditions are considered for this set of simulations: leaky duct with an R-value of 4.2 and tight duct with an R-value of 8. The percentage of leakage for a tight duct is considered as 8% and 36% for the leaky duct. The fraction of lighting heat to the conditioned space is considered to be 100%.

Parametric runs are performed for the following conditions:

- “Under deck” insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.
- “Under deck” insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- “Above deck” insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.

- "Above deck" insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- Drywall-ventilated" uninsulated roof deck and **uninsulated** plenum walls with an insulated drywall (low infiltration leakage area) ceiling with ventilated plenum.
- "90% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **90%** of the t-bar ceiling area insulated with ventilated plenum. Air leakage through the ceiling uses the FSEC values.
- "80% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **80%** of the t-bar ceiling area insulated with ventilated plenum. Air leakage through the ceiling uses the FSEC values.
- "70% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **70%** of the t-bar ceiling area insulated with ventilated plenum. Air leakage through the ceiling uses the r FSEC values.
- "60% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **60%** of the t-bar ceiling area insulated with ventilated plenum. Air leakage through the ceiling uses the FSEC values.
- "50% lay-in" uninsulated roof deck and **uninsulated** plenum walls with **50%** of the t-bar ceiling area insulated with ventilated plenum. Air leakage through the ceiling uses the FSEC values.

Results

Cooling and Heating Loads

The total cooling and heating loads (KBtu/sqft) are plotted for the various insulation conditions and climate zones that are simulated using the DOE-2 model. The total TDV (for a 30 year period) and TDV savings are also plotted. The graphs of all the results are shown in Appendix B.

Benefit Cost Ratio

The benefit cost analysis is done based on the TDV savings and the difference in the material costs of all the roofing insulation options as compared to lay-in insulation costs. The following tables show the benefit cost ratios for climate zone 3, along with a summary of benefit cost ratio of all the five climate zones under study. The benefit cost ratios for climate zones 6,10,12, and 14 are in Appendix B.

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft, and 15ft.

Table 33 shows the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof decks, drywall, and lay-in ceiling conditions for climate zone 3. The benefit cost ratios are calculated for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft. The calculation method is described in the Benefit Cost Ratio of the Mass Building with Troffers section.

The insulated drywall and lay-in ceilings show cost effectiveness for all plenum heights. Among the insulated roof decks, the ones with insulated plenum walls show no cost effectiveness for all plenum heights. The roof decks with uninsulated plenum wall show cost effectiveness for plenum heights 9 ft and above.

Table 33 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft -Climate Zone 3

CTZ3 Cost Benefit for Tightening Ducts for all insulation conditions						
	Insulated Plenum Wall		***Uninsulated Plenum Wall***			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V	Lay-in-V
3	**0.67**	**0.63**	**0.90**	**0.81**	3.61	2.79
6	**0.72**	**0.67**	1.07	**0.97**	3.40	2.85
9	**0.75**	**0.71**	1.21	1.10	3.23	2.88
12	**0.79**	**0.75**	1.32	1.20	3.10	2.91
15	**0.82**	**0.78**	1.41	1.30	2.99	2.94

Table 34 shows a summary of benefit cost ratios for tightening the ducts for roof decks and drywall ceiling for all climate zones based on which plenum heights show cost effectiveness. In this table, “All” represents cost effectiveness for all plenum heights; “>3’”, “>6’”, and “>9’” represents cost effectiveness above 3 ft, 6 ft and 9 ft of plenum height. Tightening of ducts is cost effective for insulated drywall and lay-in ceilings for all plenum heights in all climate zones. In the case of roof decks with uninsulated plenum walls, both the under deck and above deck insulated roofs show cost effectiveness for all plenum heights for climate zones 10, 12, and 14. The results for under and above deck insulate roofs with insulated plenum walls are also shown in the table.

Table 34 -- Summary of Cost Effectiveness of Tightening and Adding Insulation to Ducts for Insulated Roofs, and Drywall and Lay-In Ceilings from Leaky (R4.2) to Tight (R8) for Plenums with Leaky Ducts with Tight Ducts (R8) for Climate Zones 3, 6, 10, 12, and 14 Based on Which Plenum Heights Show a Cost Effectiveness

Summary-Cost effectiveness of tightening ducts						
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V	Lay-in-V
CTZ3	None	None	>3'	>6'	All	All
CTZ6	None	None	>3'	>6'	All	All
CTZ10	>3'	>6'	All	All	All	All
CTZ12	>9'	>12'	All	All	All	All
CTZ14	All	>3'	All	All	All	All

2. Benefit cost ratio of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceiling with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft, and 15ft.

The second case determines benefit cost ratios of insulated roof deck conditions with leaky ducts (R4.2) versus insulated lay-in ceilings with tight ducts (R 8). This benefit cost ratio is calculated for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15ft.

Table 35 shows that for climate zone 3 the under deck insulated roof with uninsulated plenum wall is cost effective for all plenum heights while the above deck insulated roof with uninsulated plenum wall shows cost effectiveness for plenum heights below 12 ft. Above deck insulated roofs with insulated plenum walls are not cost effective for any plenum heights. Under deck insulated roofs with insulated plenum walls are cost effective for plenum heights under 9 ft.

Table 35 -- Benefit Cost Ratios of Insulated Roofs with Leaky Ducts (R4.2) Versus Insulated Lay-In Ceilings with Tight Ducts (R 8) for Plenum Heights 3 ft, 6 ft, 9 ft, 12 ft and 15 ft -Climate Zone 3

CTZ3 Benefit cost of Leaky roofs vs tight layin ceilings				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	4.00	**0.92**	Infinite *	1.47
6	1.36	**0.53**	Infinite *	1.22
9	**0.62**	**0.31**	Infinite *	1.02
12	**0.30**	**0.18**	Infinite *	**0.84**
15	**0.14**	**0.10**	Infinite *	**0.69**

(Note: infinite* indicates immediate cost benefit)

Table 36 shows the summary of cost effectiveness for insulated roof decks versus insulation lay-in ceilings for climate zones 3, 6, 10, 12, and 14 based on which plenum heights show cost effectiveness. In the table below, “None” represents no cost effectiveness for any of the plenum heights; “All” represents cost effectiveness for all plenum heights, “<6’”, “<9’”, “<12’” and “<15’” represents cost effectiveness below 6 ft, 9 ft, 12 ft and 15 ft of plenum height. Here, the under deck insulated roofs with uninsulated plenum walls are cost effective for all plenum heights and for all climate zones. Under deck insulated roofs with insulated plenum walls are cost effective for all plenum heights for climate zones 10 and 14. The results for other climate zones for under deck insulated roofs with insulated plenum walls and above deck insulated roofs with uninsulated and insulated plenums are shown in the table.

Table 36 -- Summary of Cost Effectiveness of Insulated Roofs with Leaky Ducts Versus Insulated Lay-In Ceilings with Tight Ducts for Climate Zones 3, 6, 10, 12, and 14 Based on Which Plenum Heights Show Cost Effectiveness

Summary-Cost effectiveness of leaky roofs vs tight lay-in ceiling				
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
CTZ3	<9'	none	All	<9'
CTZ6	<6'	3'	All	All
CTZ10	All	<12'	All	<15'
CTZ12	<15'	<12'	All	<15'
CTZ14	All	<15'	All	<15'

3. *Benefit cost ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).*

Table 37 shows the benefit cost ratios for climate zone 3 for insulated roof decks and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft.

The results show that the under deck insulated roof with uninsulated plenum walls are cost effective for all plenum heights while the above deck insulated roof with uninsulated plenum walls is cost effective for plenum heights below 12 ft. In the case of insulated plenum wall conditions, the under deck insulated roof shows cost effectiveness for plenum height under 9 ft while the above deck insulated roof shows no cost effectiveness. The drywall ceiling is not cost effective for any plenum heights.

Table 37 -- Benefit Cost Ratio of Insulated Roofs/Drywall Ceiling With Tight Ducts (R 8) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights of 3 ft, 6 ft, 9 ft, 12 ft and 15 ft- Climate Zone 3

CTZ3 Cost Benefit Ratio- Tight Ducts (R 8)					
	Insulated Plenum Wall		***Uninsulated Plenum Wall***		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V
3	2.01	**0.85**	4.30	1.28	**0.57**
6	1.09	**0.56**	3.87	1.15	**0.46**
9	**0.66**	**0.39**	3.51	1.04	**0.37**
12	**0.43**	**0.27**	3.19	**0.95**	**0.30**
15	**0.29**	**0.20**	2.92	**0.87**	**0.25**

Table 38 shows a summary of cost effectiveness of insulated roof decks and drywall ceilings with tight ducts versus insulated lay-in ceilings with tight ducts for climate zones 3, 6, 10, 12, and 14 based on which plenum heights show cost effectiveness. In the table below, “None” represents no cost effectiveness for any of the plenum heights; “All” represents cost effectiveness for all plenum heights, “<6’”, “<9’”, “<12’” and “<15’” represents cost effectiveness below 6 ft, 9 ft, 12 ft and 15 ft of plenum height. The results indicate that the under deck insulated roof with uninsulated plenums are cost effective for all plenum heights and for all climate zones. The ventilated plenum drywall case shows cost effectiveness for all plenum heights in climate zone 14 and for plenum heights less than 9 ft for climate zone 12 and less than 12 ft for climate zone 10. The results for under deck insulated roofs with insulated plenum walls, and above deck insulated roofs with insulated and uninsulated plenum walls are shown in the table.

Table 38 -- Summary of Cost Effectiveness of Insulated Roofs and Drywall Ceilings With Tight Ducts Versus Insulated Lay-In Ceilings With Tight Ducts for Climate Zones 3, 6, 10, 12, and 14 Based on Which Plenum Heights Show Cost Effectiveness

Summary-Cost effectiveness of tight roofs/drwall ceiling vs tight lay-in ceiling					
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V
CTZ3	<9'	None	All	<12'	None
CTZ6	<6'	<6'	All	All	None
CTZ10	All	<12'	All	All	<12'
CTZ12	<15'	<12'	All	All	<9'
CTZ14	All	<15'	All	All	All

Wood Frame Wall With Pendant Lighting

Description of Building Parametrics

In the case of the frame wall building with pendant lighting, all conditions of the building are identical to the mass wall with pendant lighting case study. The only changed parameter is the wall construction of the plenum walls. The wood frame plenum wall consists of the following building components: stucco as the exterior finish, ½ in. plywood board, and fiber glass batt insulation (R11 or R13 depending on climate zones). Here, the roof decks with uninsulated plenum wall have not been analyzed since the wall type is of wood frame construction, which is required to be insulated below an insulated roof. Two climate zones, 3 and 12, sre considered for this frame wall study.

Parametric runs are performed for the following conditions:

- "Under deck" insulated roof with **insulated** plenum walls and an uninsulated t-bar ceiling.
- "Under deck" insulated roof with **uninsulated** plenum walls and an uninsulated t-bar ceiling.
- Drywall-ventilated" uninsulated roof deck and **uninsulated** plenum walls with an insulated drywall (low infiltration leakage area) ceiling with ventilated plenum.

Results

Cooling and Heating Loads

The total cooling and heating loads (KBtu/sqft) are plotted for the various insulation conditions for climate zone 3 and 12. The total TDV (for a 30 year period) and TDV savings are also plotted. The graphs of all the results for climate zone 3 are shown in Appendix C.

Benefit Cost

The benefit cost analysis was done based on the TDV savings and the difference in the material costs of all the roofing insulation options as compared to lay-in insulation costs. The following tables show the benefit cost ratios for climate zone 3, along with a summary of benefit cost ratio of all the five climate zones under study. The benefit cost ratios for climate zone 12 are in Appendix C.

1. ***Benefit cost ratio of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceiling from leaky (R 4.2) to tight (R 8) for plenum heights 3 ft, 6 ft, 9 ft, 12 ft, and 15ft.***

Table 39 shows the benefit cost ratios for tightening the ducts and adding duct insulation (from R 4.2 to R 8) for insulated roof deck, drywall, and lay-in ceiling conditions for climate zone 3. The benefit cost ratios are calculated for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft and 15 ft. The calculation method for this is described in the Benefit Cost Ratio of the Mass Building with Troffers section.

The drywall and lay-in ceiling shows cost effectiveness for all plenum heights. The above deck insulated roofs, are cost effective for plenum heights 15 ft and above. The under deck insulated roofs are cost effective for plenum heights 12 ft and above.

Table 39 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3 ft, 6 ft, 9 ft, 12 ft, and 15ft -Climate Zone 3

CTZ3				
Benefit cost ratio for Tightening Ducts for all insulation conditions				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V	Lay-in-V
3	**0.76**	**0.71**	4.33	3.13
6	**0.84**	**0.79**	4.59	3.46
9	**0.93**	**0.88**	4.83	3.76
12	1.02	**0.96**	5.03	4.04
15	1.10	1.05	5.22	4.30

Table 40 shows the summary of benefit cost ratios for tightening the ducts for roof decks and drywall ceiling for climate zones 3 and 12 based on which plenum heights show cost effectiveness. In the table below, "None" represents no cost effectiveness for any of the plenum heights; "All" represents cost effectiveness for all plenum heights, "<6'", "<9'", "<12'" and "<15'" represents cost effectiveness below 6 ft, 9 ft, 12 ft and 15 ft of plenum height. Tightening of ducts is cost effective for insulated ceilings for all plenum heights in all climate zones. The under deck insulated roof shows cost effectiveness above plenum height 9 ft for climate zone 3 and above 3 ft for climate zone 12. The above deck insulated roofs shows cost effectiveness for plenum heights above 12 ft for climate zone 3 and above 3 ft for climate zone 12.

Table 40 -- Summary of Cost Effectiveness of Insulated Roofs with Leaky Ducts Versus Insulated Lay-In Ceiling With Tight Ducts for Climate Zones 3 and 12 Based on Which Plenum Heights Show Cost Effectiveness

Summary-Cost effectiveness of tightening ducts				
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V	Lay-in-V
CTZ3	>9'	>12'	All	All
CTZ12	>3'	>6'	All	All

2. ***Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15ft.***

The second case determines benefit cost ratios for insulated roof deck conditions with leaky ducts (R4.2) versus insulated lay-in ceilings with tight ducts (R 8). The benefit cost ratios are calculated for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft, and 15 ft.

Table 41 shows that for climate zone 3 the under deck insulated roofs are cost effective for all plenum heights while the above deck insulated roofs is cost effective for plenum heights below 12 ft.

Table 41 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3 ft, 6 ft, 9 ft, 12 ft And 15 ft- Climate Zone 3

CTZ3 Benefit cost ratio for Leaky roofs vs tight layin ceilings		
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.
3	8.15	1.43
6	3.96	1.20
9	2.58	1.03
12	1.89	**0.89**
15	1.47	**0.78**

Table 42 shows a summary of cost effectiveness of insulated roof decks with leaky ducts versus insulated lay-in ceilings with tight ducts for climate zones 3 and 12 based on which plenum heights show cost effectiveness. In the table below, “All” represents cost effectiveness for all plenum heights; “<12’” represents cost effectiveness below 12 ft of plenum height. The results indicate that the under deck insulated roof are cost effective for all plenum heights and for all climate zones. Above deck insulated roofs are cost effective for all plenum heights in climate zone 12 and for plenum heights less than 12 ft in climate zone 3.

Table 42 -- Summary Of Cost Effectiveness of Insulated Roofs With Leaky Ducts Versus Insulated Lay-In Ceilings With Tight Ducts for Climate Zones 3 and 12 Based on Which Plenum Heights Show Cost Effectiveness

Summary-Cost effectiveness of leaky roofs vs tight lay-in ceiling		
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.
CTZ3	All	<12'
CTZ12	All	All

3. ***Benefit cost ratio for insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8)***

Table 43 shows the benefit cost ratios for climate zone 3 for insulated roof decks and drywall ceilings with tight ducts (R 8) versus insulated lay-in ceilings with tight ducts for the plenum heights of 3 ft, 6 ft, 9 ft, 12 ft and 15 ft.

The results show that the under deck insulated roofs are cost effective for all plenum heights while the above deck insulated roofs are cost effective for plenum heights below 9 ft. The insulated drywall ceilings are not cost effective for any plenum heights.

Table 43 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft And 15ft- Climate Zone 3

CTZ3 Benefit cost ratio- Tight Ducts (R 8)			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V
3	3.18	1.24	**0.79**
6	2.40	1.11	**0.83**
9	1.92	**1.00**	**0.86**
12	1.60	**0.91**	**0.89**
15	1.36	**0.82**	**0.92**

Table 44 shows a summary of cost effectiveness of insulated roof decks and drywall ceilings with tight ducts versus insulated lay-in ceilings with tight ducts for climate zones 3 and 12 based on which plenum heights show cost effectiveness. The results indicate that the under deck insulated roofs are cost effective for all plenum heights. Above deck insulated roofs are cost effective for all plenum heights in climate zone 12 and for plenum heights less than 9 feet in climate zone 3. Insulated drywall ceilings are cost effective for all plenum heights in climate zone 12 but are not cost effective for any plenum heights in climate zone 3.

Table 44 -- Summary of Cost Effectiveness of Insulated Roofs and Drywall Ceilings With Tight Ducts Versus Insulated Lay-In Ceilings With Tight Ducts for Climate Zones 3, 6, 10, 12 and 14 Based on Which Plenum Heights Show Cost Effectiveness

Summary-Cost effectiveness of tight roofs/drwall ceiling vs tight lay-in ceiling			
Climate Zones	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling- V
CTZ3	All	<9'	None
CTZ12	All	All	All

Recommendations

In evaluating the cost effectiveness of requiring insulation at the roof deck in lieu of lay-in insulation above t-bar ceilings, the following principles are applied:

- Only below deck insulation is considered. Above deck insulation is more expensive than below deck insulation. Above deck insulation is chosen primarily to protect single ply roofing systems over certain deck materials (such as metal decks). Above deck insulation is also often used in conjunction with return plenums or when the roof deck is exposed to view. The cost effectiveness analysis need not pay for the other amenities yielded by above deck insulation. Below deck insulation is the least cost method of providing the energy savings from roof insulation.
- Desirability of a single insulation position requirement. In mild climates, the benefits from insulating the roof deck are less and are cost-justified for a smaller range of plenum heights in mass buildings. However, insulating the roof decks of frame wall construction buildings are cost-justified in all climate zones. Having insulation position requirements that are a function of wall construction and climate zone seem to be an unnecessary complexity that hinders compliance and enforcement of the building standards.
- Desirability of allowing lay-in insulation for small conditioned offices or other spaces in unconditioned warehouse and industrial buildings. The cost of framing in the perimeter of these spaces up to a 12 ft or higher ceiling plenum is not cost effective.

The results sections in this report for each wall construction type detail the cost effectiveness of various combinations of climate zone, wall mass, fixture type, etc. The general conclusions for cost effectiveness are:

- For mild climates (CTZ 3, 6): roof insulation is cost effective when the plenum heights in mass buildings are less than 9 ft tall and is cost-effective for all plenum heights in frame buildings.
- For warmer climates (CTZ 10, 12, 14): roof insulation is cost effective for all wall types for plenum heights up to 12 ft tall and in some cases (such as frame walls and mass walls not needing insulation) up to the maximum height considered, 15 feet.

Given that most of the nonresidential construction activity is occurring in the warmer climate zones and the consideration discussed above, it is decided that 12 ft is an appropriate plenum height above which lay-in insulation would be acceptable.

Language for the ACM manual needs to be developed so that when the plenum is greater than 12 ft and users choose to install insulation at the ceiling using the performance approach, the ACM manual will model the appropriate air leakage for ceilings and will account for expected problems in the misplacement of ceiling insulation on t-bar ceilings over the building's useful life. The appropriate multipliers or algorithms will be derived from this report and the separate report on duct tightening proposed for the 2005 Standards.

Proposed Standards Language

A new subsection (g) on nonresidential roof and ceiling insulation placement is proposed for addition to the mandatory insulation requirements in Section 118 as shown below.

SECTION 118 - MANDATORY REQUIREMENTS FOR INSULATION AND COOL ROOFS

(g) Nonresidential and high-rise residential roof/ceiling insulation placement. Insulation installed to limit heat loss and gain through the top of conditioned spaces shall be at the roof, either above or below the roof deck and shall be placed in direct contact with the roof deck. Insulation placed on top of a ceiling shall be deemed to have no affect on envelope heat loss.

Exception to Section 118(g): When the average height of the space between the ceiling and the roof is greater than 12 feet, insulation placed in direct contact with the ceiling shall be an acceptable method of reducing heat loss from a conditioned space and shall be accounted for in heat loss calculations.

Section 118 is part of Subchapter 2 *"All Occupancies—Mandatory Requirements for the Manufacture, Construction and Installation Of Systems, Equipment And Building Components"* thus the title of 118(e) needs to delineate that this insulation requirement is for nonresidential and high-rise residential buildings only and not for all occupancies. Given that the proposed insulation position requirements do not apply to low-rise residential buildings, the above code language could be applied to a new section (Section 125) under Subchapter 3, *"Nonresidential, High-Rise Residential, and Hotel/Motel Occupancies—Mandatory Requirements For Space-Conditioning and Service Water-Heating Systems"*. Currently the title to Subchapter 3 makes no mention of building envelopes, thus if the above code language were to be applied to Section 125, Subchapter 3 should be renamed, *"Nonresidential, High-Rise Residential, and Hotel/Motel Occupancies—Mandatory Requirements For Space-Conditioning, ~~and~~ Service Water-Heating Systems and Building Envelopes."*

If the insulation position requirements were placed in Section 125, the proposed code language would read as follows:

SECTION 125 - REQUIREMENTS FOR ROOF/CEILING INSULATION PLACEMENT

Insulation installed to limit heat loss and gain through the top of conditioned spaces shall be at the roof, either above or below the roof deck and shall be placed in direct contact with the roof deck. Insulation placed on top of a ceiling shall be deemed to have no affect on envelope heat loss.

EXCEPTION to Section 125: When the average height of the space between the ceiling and the roof is greater than 12 feet, insulation placed in direct contact with the ceiling shall be an acceptable method of reducing heat loss from a conditioned space and shall be accounted for in heat loss calculations.

Section 143 should be amended as shown below to alert users of the Standards to the affect of this new mandatory measure on prescriptively complying with the envelope requirements. If the mandatory requirements for insulation position are placed in Section 125 instead of 118(g), then substitute 125 for 118(g) in the wording below.

SECTION 143 – PRESCRIPTIVE REQUIREMENTS FOR BUILDING ENVELOPES

A building complies with this section by being designed with and having constructed and installed either (1) envelope components that comply with each of the requirements in Subsection (a) for each individual component, or (2) an envelope that complies with the overall requirements in Subsection (b). When making calculations under Subsection (a) or (b), all of the rules listed in Section 141 (c) 1, 4, and 5 shall apply.

(a) **Envelope Component Approach**.

1. **Exterior roofs and ceilings.** Exterior roofs (and ceilings where allowed in Section 118(g)) shall have either an installed insulation R-value no less than, or an overall assembly U-factor no greater than, the applicable value in Table 1-H or 1-I.

Proposed Changes to the Nonresidential Manual

Section 3.2.1 Envelope Design Procedures: **Mandatory Measures** should be updated to describe allowable placement of roof/ceiling insulation. This section should include a sketch showing that above or below deck insulation is acceptable as long as there is direct contact with the roof deck. Another sketch should show an allowed insulated ceiling when plenum heights are greater than 12 ft tall. The insulated ceiling sketch should show that duct testing and tightening are required for single zone systems and the text should reference the proposed duct tightening requirements in Section 144.

Section 3.2.2A Exterior Roof and Ceilings should be edited with the proviso that insulating ceilings only counts towards fulfilling the envelope requirements when plenum heights are above 12 ft.

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Appendix A -- Mass Wall with Troffers

Energy Analysis

The graphs here refer to mass wall buildings with fluorescent troffers. In all cases except the drywall ceiling, the lighting is recessed troffers with 30% of lighting power is rejected to the plenum and 70% of lighting power remains in the conditioned space. Drywall spaces are modeled with surface-mounted troffers and 10% of lighting heat is rejected to the plenum and 90% stays in he conditioned space.

Effects of Insulation Location on Cooling Loads

The results of cooling loads for all climate zones with leaky ducts (R 4.2 insulation) are shown below. The results of the cooling loads with tight ducts (R 8) are not shown since it was observed that the cooling and heating loads of all insulating conditions for tight ducts (R 8) showed comparable results with the cooling and heating loads for the leaky duct condition.

Climate Zone 3

The location of the insulation on the roof deck versus the ceiling showed the following results on the total cooling loads of the building. As the plenum height increases from 3 feet to 15 feet, there is a decrease in the total cooling loads for all the various insulation conditions. The unventilated drywall insulated ceiling showed maximum cooling loads when compared to the rest of the insulation conditions. This could be attributed to the fact that not ventilating the plenum space actually prevents the heat loss from the conditioned space and hence increases the cooling loads on the building. The cooling loads for the two roof -deck insulation conditions (above deck and under deck) with plenum walls uninsulated had the lowest values for the cooling loads as compared to the other insulation conditions (both showed almost the same cooling loads). When comparing the insulated roof decks, the ones with plenum wall insulated had higher cooling loads than the ones with uninsulated plenum walls. The three lay-in insulation conditions had cooling loads lower than the two dry-wall insulations but higher than the roof deck insulation conditions. Among the lay-in conditions, the unventilated lay-in insulated ceiling had a higher cooling load than the ventilated lay-in ceilings.

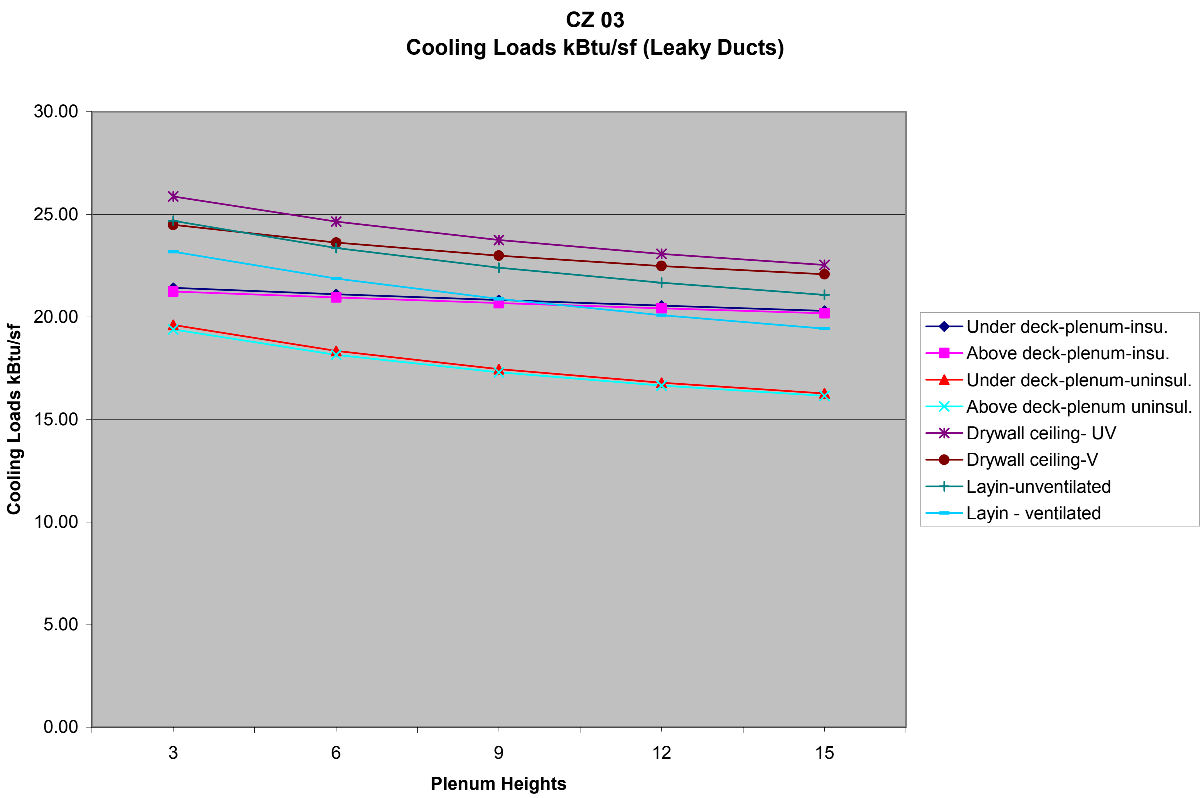

Figure 11 -- Cooling Loads (Kbtu/sqft) for Climate Zone 3 with Leaky Duct Condition and R 4.2 Insulation

Effects of Insulation Position on Heating Loads

Climate Zone 3

The heating loads showed a very small increase with the increase in the plenum heights for all the insulation conditions, except for roof decks with uninsulated plenum walls. Maximum heating loads were observed in case of the ventilated lay-in insulation ceiling. This could be attributed to the high ventilation rates being used in this case. The roof decks with uninsulated plenum wall had higher heating loads than the unventilated lay-in ceiling. The insulated under deck and above deck roofs with uninsulated plenum walls had higher heating loads than the ventilated drywall ceiling. This could be attributed to the heat escape due to the absence of insulation on plenum walls. The under deck and above deck roofs with insulated plenum walls and the unventilated drywall ceiling had the lowest heating loads when compared to the other insulation conditions.

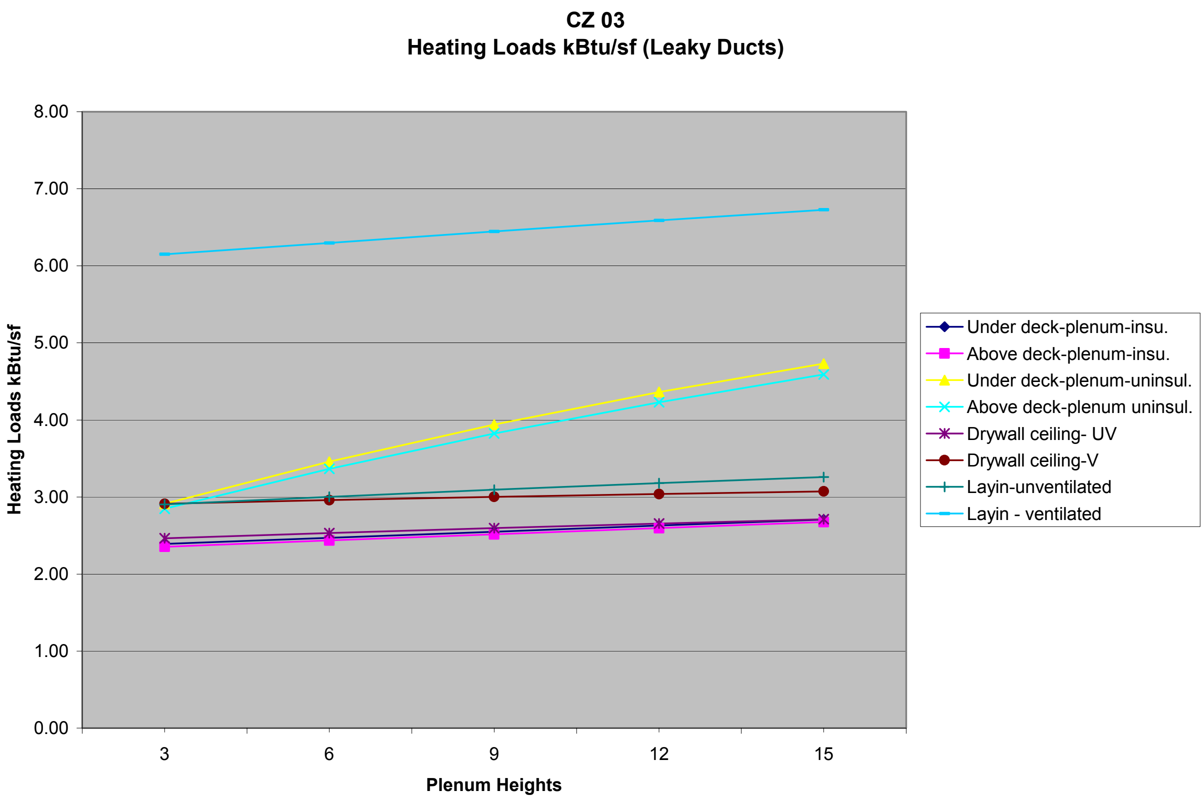

Figure 12 -- Heating Loads (Kbtu/Sqft) for Climate Zone 3 With Leaky Ducts and R 4.2 Insulation

Effects of Insulation Position on TDV Savings

The TDV savings for insulated roof decks and drywall ceiling were analyzed related to the lay-in insulated and ventilated acoustic tile ceilings. The TDV savings for climate zone 3 with leaky ducts (R 4.2 insulation) is described below. Similar patterns were observed for the case with tight ducts with R 8 insulation and so have not been described in this report.

Climate Zone 3

In case of the ventilated lay-in ceiling conditions, the TDV savings for all the insulation conditions decreases with the increase in the plenum heights. The roof decks with uninsulated plenum walls showed maximum TDV savings of which the one with the above deck roof conditions had the maximum value. This could be attributed to these conditions having lower cooling loads than the other insulated roofs/ceilings. The insulated roof decks with insulated plenum walls were observed to have less TDV savings than the ones with uninsulated plenum walls. Both the ventilated and unventilated drywall ceilings showed the lowest TDV savings.

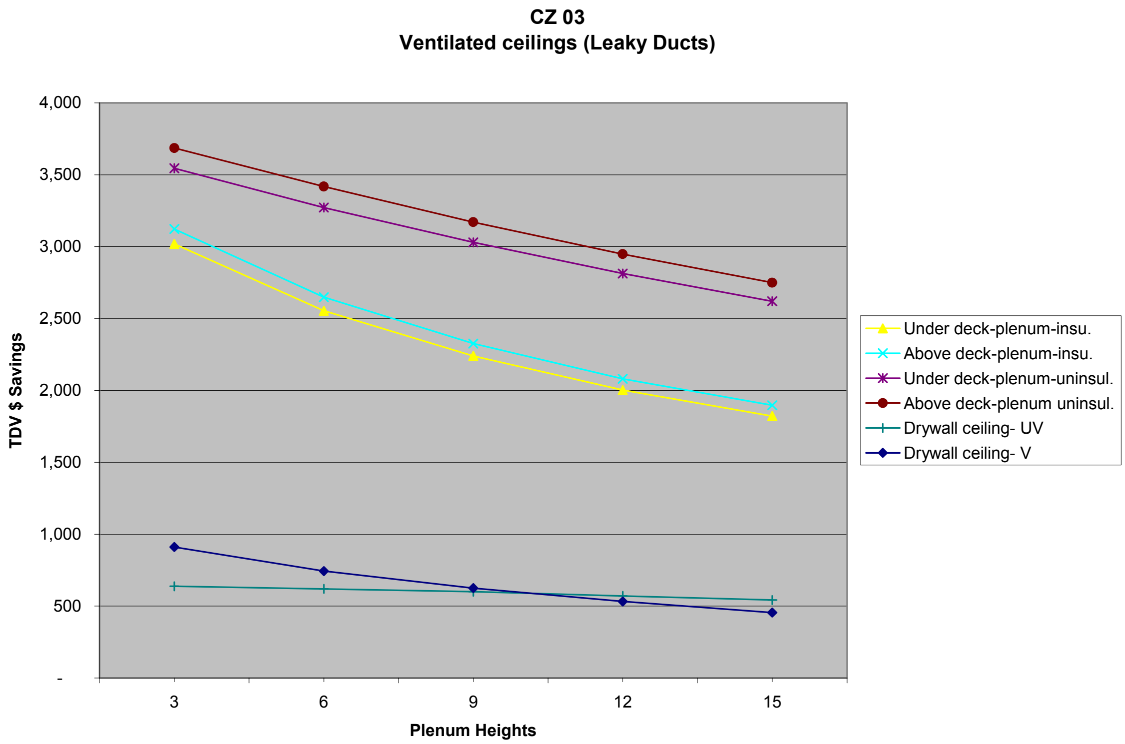

Figure 13 -- TDV Savings ($) for Climate Zone 3 With Leaky Ducts and R 4.2 Insulation

Benefit Cost Ratio

Climate Zone 6

1. ***Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft, and 15ft.***

Table 45 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 6

CTZ6
Benefit cost ratio for Tightening Ducts for all insulation conditions

	Insulated Plenum Wall		*Uninsulated Plenum Wall*					
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V	Lay-in- UV	Lay-in-V
3	**0.97**	**0.91**	1.28	1.15	4.15	4.79	3.98	3.64
6	1.04	**0.99**	1.56	1.42	4.02	4.60	3.88	3.68
9	1.11	1.06	1.73	1.59	3.88	4.44	3.76	3.71
12	1.16	1.12	1.83	1.70	3.75	4.32	3.65	3.74
15	1.21	1.18	1.92	1.79	3.64	4.21	3.55	3.74

2. ***Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.***

Table 46 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 6

CTZ6
Benefit cost ratios of Leaky roofs vs Tight layin ceilings

	Insulated Plenum Wall		*Uninsulated Plenum Wall*	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	2.20	1.02	49.96	2.73
6	**0.45**	**0.29**	37.49	2.12
9	**(0.03)**	**(0.02)**	28.32	1.65
12	**(0.21)**	**(0.14)**	21.15	1.28
15	**(0.29)**	**(0.23)**	15.23	**0.97**

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 47 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 6

CTZ6 Benefit cost ratio Ratio- Tight Ducts (R 8)						
	Insulated Plenum Wall		*Uninsulated Plenum Wall*			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	1.49	**0.98**	3.53	1.92	**0.17**	**0.39**
6	**0.70**	**0.50**	3.22	1.76	**0.12**	**0.26**
9	**0.33**	**0.25**	2.96	1.62	**0.06**	**0.17**
12	**0.15**	**0.10**	2.73	1.50	**0.01**	**0.09**
15	**0.04**	**0.03**	2.53	1.39	**(0.04)**	**0.02**

Climate Zone 10

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft.

Table 48 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 10

CTZ10 Benefit cost for Tightening Ducts for all insulation conditions								
	Insulated Plenum Wall		*Uninsulated Plenum Wall*					
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V	Lay-in- UV	Lay-in-V
3	1.05	**0.95**	1.62	1.42	7.17	8.09	7.01	5.64
6	1.15	1.06	2.24	1.97	7.26	7.97	7.12	5.90
9	1.25	1.16	2.73	2.42	7.31	7.88	7.18	6.14
12	1.34	1.25	3.14	2.81	7.35	7.83	7.23	6.34
15	1.44	1.35	3.48	3.16	7.36	7.81	7.26	6.53

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 49 -- Benefit Cost Ratio of Insulated Roofs with Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 10

CTZ10 Benefit costs of Leaky roofs versus Tight layin ceilings				
	Insulated Plenum Wall		*Uninsulated Plenum Wall*	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	8.92	2.19	Infinite *	2.77
6	3.52	1.42	Infinite *	2.04
9	1.90	**0.97**	Infinite *	1.50
12	1.16	**0.69**	Infinite *	1.05
15	**0.76**	**0.50**	Infinite *	**0.69**

3. Benefit cost ratio for insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 50 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 10

CTZ10 Benefit cost Ratio- Tight Ducts (R8)						
	Insulated Plenum Wall		*Uninsulated Plenum Wall*			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	4.40	1.89	7.95	2.37	**0.81**	1.04
6	2.57	1.35	6.75	2.02	**0.76**	**0.93**
9	1.70	1.01	5.88	1.77	**0.72**	**0.85**
12	1.21	**0.78**	5.22	1.57	**0.69**	**0.78**
15	**0.90**	**0.62**	4.69	1.41	**0.65**	**0.73**

Climate Zone 12

1. ***Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft.***

Table 51 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings From Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 12

CTZ12
Benefit costs of tightening the ducts

	Insulated Plenum Wall		***Uninsulated Plenum Wall***					
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V	Lay-in- UV	Lay-in-V
3	**0.87**	**0.79**	1.31	1.15	5.72	6.72	5.62	4.81
6	**0.95**	**0.87**	1.85	1.62	5.84	6.65	5.76	5.06
9	1.03	**0.96**	2.31	2.05	5.91	6.62	5.85	5.28
12	1.08	1.01	2.71	2.42	5.95	6.60	5.93	5.49
15	1.15	1.09	3.09	2.79	5.99	6.60	6.00	5.70

2. ***Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.***

Table 52 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 12

CTZ12
Benefit costs of Leaky roofs vs tight layin ceilings

	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	7.99	1.95	Infinite *	2.51
6	3.26	1.30	Infinite *	1.90
9	1.83	**0.93**	Infinite *	1.39
12	1.19	**0.70**	Infinite *	**0.99**
15	**0.83**	**0.53**	Infinite *	**0.64**

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 53 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 12

CTZ12 Benefit cost Ratio- Tight Ducts (R 8)						
	Insulated Plenum Wall		*Uninsulated Plenum Wall*			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	3.89	1.67	7.10	2.11	**0.87**	1.04
6	2.33	1.22	6.08	1.81	**0.84**	**0.95**
9	1.59	**0.93**	5.30	1.59	**0.82**	**0.89**
12	1.16	**0.75**	4.71	1.41	**0.80**	**0.85**
15	**0.90**	**0.61**	4.24	1.27	**0.78**	**0.81**

Climate Zone 14

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft.

Table 54 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 14

CTZ14 Benefit cost for Tightening Ducts for all insulation conditions								
	Insulated Plenum Wall		*Uninsulated Plenum Wall*					
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V	Lay-in- UV	Lay-in-V
3	1.11	1.02	1.68	1.48	7.57	8.24	7.35	5.42
6	1.21	1.12	2.32	2.02	7.74	8.20	7.56	5.81
9	1.32	1.22	2.92	2.58	7.86	8.19	7.69	6.13
12	1.41	1.32	3.45	3.08	7.94	8.19	7.80	6.43
15	1.51	1.42	3.92	3.54	8.01	8.20	7.88	6.72

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 55 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 14

CTZ14 Benefit costs of Leaky roofs versus Tight layin ceilings				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	10.28	2.51	Infinite *	3.21
6	4.22	1.69	Infinite *	2.45
9	2.38	1.21	Infinite *	1.83
12	1.53	**0.90**	Infinite *	1.30
15	1.06	**0.69**	Infinite *	**0.85**

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 56 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 14

CTZ14 Benefit cost Ratio- Tight Ducts (R 8)						
	Insulated Plenum Wall		***Uninsulated Plenum Wall***			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	5.01	2.15	9.06	2.70	1.06	1.32
6	3.02	1.58	7.77	2.33	1.04	1.23
9	2.05	1.21	6.82	2.05	1.01	1.15
12	1.50	**0.96**	6.06	1.82	**0.99**	1.09
15	1.15	**0.79**	5.46	1.64	**0.96**	1.05

Appendix B -- Mass Wall with Pendant Lighting

Energy Analysis

Effects of Insulation Location on Cooling Loads

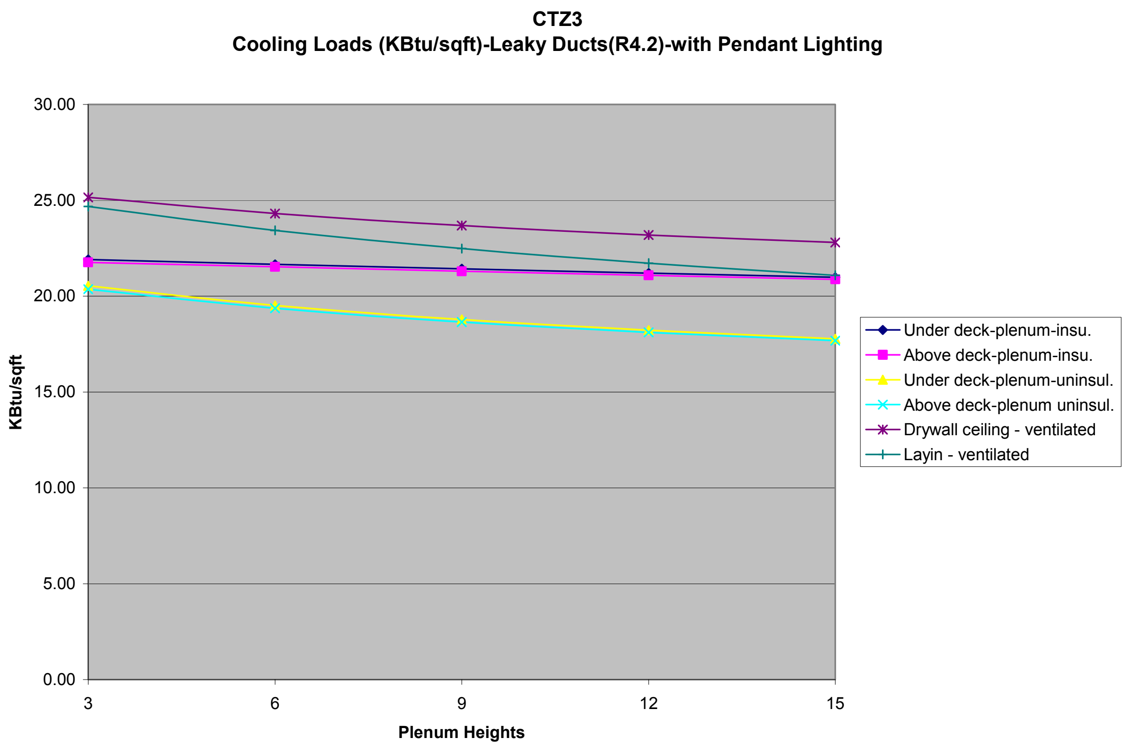

Figure 14 -- Cooling Loads, Leaky Ducts (R4.2) With Pendant Lighting

Effects of Insulation Location on Heating Loads

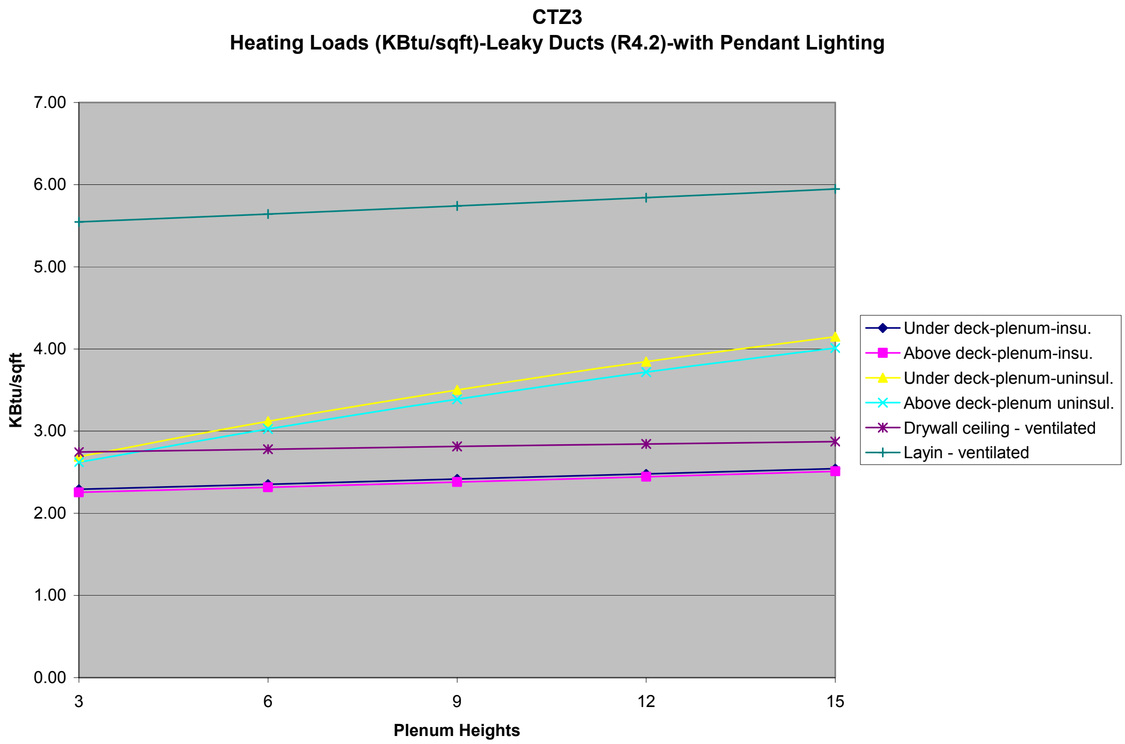

Figure 15 -- Heating Loads, Leaky Ducts (R4.2) With Pendant Lighting

Effects of Insulation Position on TDV Savings

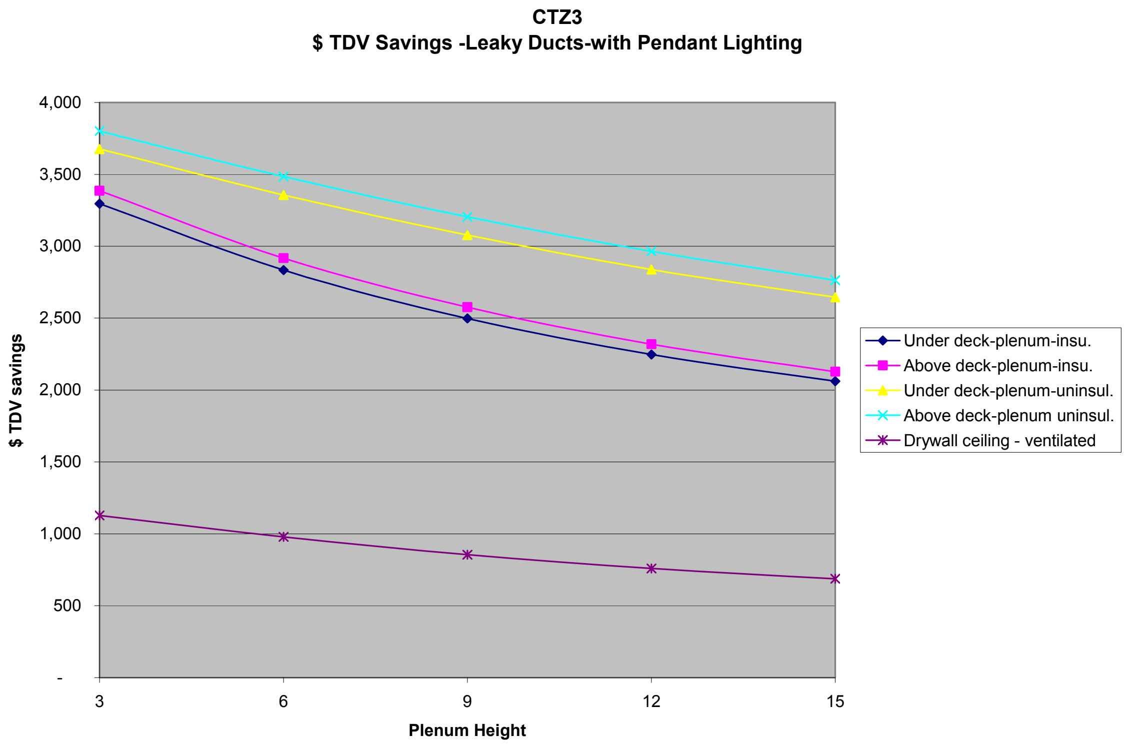

Figure 16 -- TDV Savings, Leaky Ducts With Pendant Lighting

Benefit Cost Ratio

Climate Zone 6

1. ***Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft.***

Table 57 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 6

CTZ6 Benefit cost for Tightening Ducts for all insulation conditions						
	Insulated Plenum Wall		***Uninsulated Plenum Wall***			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V	Lay-in-V
3	**0.67**	**0.63**	**0.90**	**0.81**	3.61	2.79
6	**0.72**	**0.67**	1.07	**0.97**	3.40	2.85
9	**0.75**	**0.71**	1.21	1.10	3.23	2.88
12	**0.79**	**0.75**	1.32	1.20	3.10	2.91
15	**0.82**	**0.78**	1.41	1.30	2.99	2.94

2. ***Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.***

Table 58 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 6

CTZ6 Benefit cost ratios of Leaky roofs vs Tight layin ceilings				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	2.20	1.02	49.96	2.73
6	**0.45**	**0.29**	37.49	2.12
9	**(0.03)**	**(0.02)**	28.32	1.65
12	**(0.21)**	**(0.14)**	21.15	1.28
15	**(0.29)**	**(0.23)**	15.23	**0.97**

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 59 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 6

CTZ6 Benefit cost ratio Ratio- Tight Ducts (R 8)						
	Insulated Plenum Wall		**Uninsulated Plenum Wall**			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	1.49	**0.98**	3.53	1.92	**0.17**	**0.39**
6	**0.70**	**0.50**	3.22	1.76	**0.12**	**0.26**
9	**0.33**	**0.25**	2.96	1.62	**0.06**	**0.17**
12	**0.15**	**0.10**	2.73	1.50	**0.01**	**0.09**
15	**0.04**	**0.03**	2.53	1.39	**(0.04)**	**0.02**

Climate Zone 10

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft.

Table 60 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 10

CTZ10 Benefit cost ratio for Tightening Ducts for all insulation conditions						
	Insulated Plenum Wall		**Uninsulated Plenum Wall**			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V	Lay-in-V
3	**0.99**	**0.90**	1.55	1.35	8.06	5.61
6	1.08	**1.00**	2.16	1.89	7.95	5.91
9	1.17	1.08	2.66	2.35	7.88	6.16
12	1.27	1.19	3.07	2.77	7.83	6.38
15	1.36	1.28	3.44	3.12	7.80	6.56

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 61 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 10

CTZ10 Benefit costs of Leaky roofs versus Tight layin ceilings				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	8.92	2.19	Infinite *	2.77
6	3.52	1.42	Infinite *	2.04
9	1.90	**0.97**	Infinite *	1.50
12	1.16	**0.69**	Infinite *	1.05
15	**0.76**	**0.50**	Infinite *	**0.69**

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 62 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 10

CTZ10 Benefit cost Ratio- Tight Ducts (R8)						
	Insulated Plenum Wall		***Uninsulated Plenum Wall***			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- UV	Drywall ceiling- V
3	4.40	1.89	7.95	2.37	**0.81**	1.04
6	2.57	1.35	6.75	2.02	**0.76**	**0.93**
9	1.70	1.01	5.88	1.77	**0.72**	**0.85**
12	1.21	**0.78**	5.22	1.57	**0.69**	**0.78**
15	**0.90**	**0.62**	4.69	1.41	**0.65**	**0.73**

Climate Zone 12

1. ***Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft.***

Table 63 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 12

CTZ12
Benefit cost ratio for Tightening Ducts for all insulation conditions

	Insulated Plenum Wall		*Uninsulated Plenum Wall*			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-V	Lay-in-V
3	**0.85**	**0.79**	1.29	1.15	6.67	4.77
6	**0.92**	**0.85**	1.78	1.56	6.61	5.00
9	**0.98**	**0.92**	2.25	2.00	6.58	5.24
12	1.05	**1.00**	2.65	2.37	6.56	5.45
15	1.12	1.05	3.00	2.72	6.56	5.65

2. ***Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.***

Table 64 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 12

CTZ12
Benefit costs of Leaky roofs vs tight layin ceilings

	Insulated Plenum Wall		*Uninsulated Plenum Wall*	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	7.99	1.95	Infinite *	2.51
6	3.26	1.30	Infinite *	1.90
9	1.83	**0.93**	Infinite *	1.39
12	1.19	**0.70**	Infinite *	**0.99**
15	**0.83**	**0.53**	Infinite *	**0.64**

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 65 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 12

CTZ12 Benefit cost Ratio- Tight Ducts (R 8)						
	Insulated Plenum Wall		*Uninsulated Plenum Wall*			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	3.89	1.67	7.10	2.11	**0.87**	1.04
6	2.33	1.22	6.08	1.81	**0.84**	**0.95**
9	1.59	**0.93**	5.30	1.59	**0.82**	**0.89**
12	1.16	**0.75**	4.71	1.41	**0.80**	**0.85**
15	**0.90**	**0.61**	4.24	1.27	**0.78**	**0.81**

Climate Zone 14

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft.

Table 66 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings From Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 14

CTZ14 Benefit cost ratio for Tightening Ducts for all insulation conditions						
	Insulated Plenum Wall		*Uninsulated Plenum Wall*			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling- V	Lay-in-V
3	1.08	**0.99**	1.64	1.45	8.22	5.41
6	1.17	1.09	2.28	2.00	8.18	5.79
9	1.26	1.18	2.87	2.54	8.18	6.13
12	1.36	1.28	3.40	3.03	8.18	6.43
15	1.44	1.36	3.86	3.50	8.20	6.70

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 67 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 14

CTZ14 Benefit costs of Leaky roofs versus Tight layin ceilings				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.
3	10.28	2.51	Infinite *	3.21
6	4.22	1.69	Infinite *	2.45
9	2.38	1.21	Infinite *	1.83
12	1.53	**0.90**	Infinite *	1.30
15	1.06	**0.69**	Infinite *	**0.85**

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 68 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 14

CTZ14 Benefit cost Ratio- Tight Ducts (R 8)						
	Insulated Plenum Wall		***Uninsulated Plenum Wall***			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Under deck-plenum-uninsul.	Above deck-plenum uninsul.	Drywall ceiling-UV	Drywall ceiling-V
3	5.01	2.15	9.06	2.70	1.06	1.32
6	3.02	1.58	7.77	2.33	1.04	1.23
9	2.05	1.21	6.82	2.05	1.01	1.15
12	1.50	**0.96**	6.06	1.82	**0.99**	1.09
15	1.15	**0.79**	5.46	1.64	**0.96**	1.05

Appendix C -- Frame Wall Building with Pendant Lighting

Energy Analysis

Effects of Insulation Location on Cooling Loads

Climate Zone 3

An increase in the cooling loads was observed with the increase in the plenum heights, except in case of roof deck with insulated plenum wall, which showed almost a constant value with increasing heights. The lay-in insulated ceiling was observed to have the highest cooling loads.

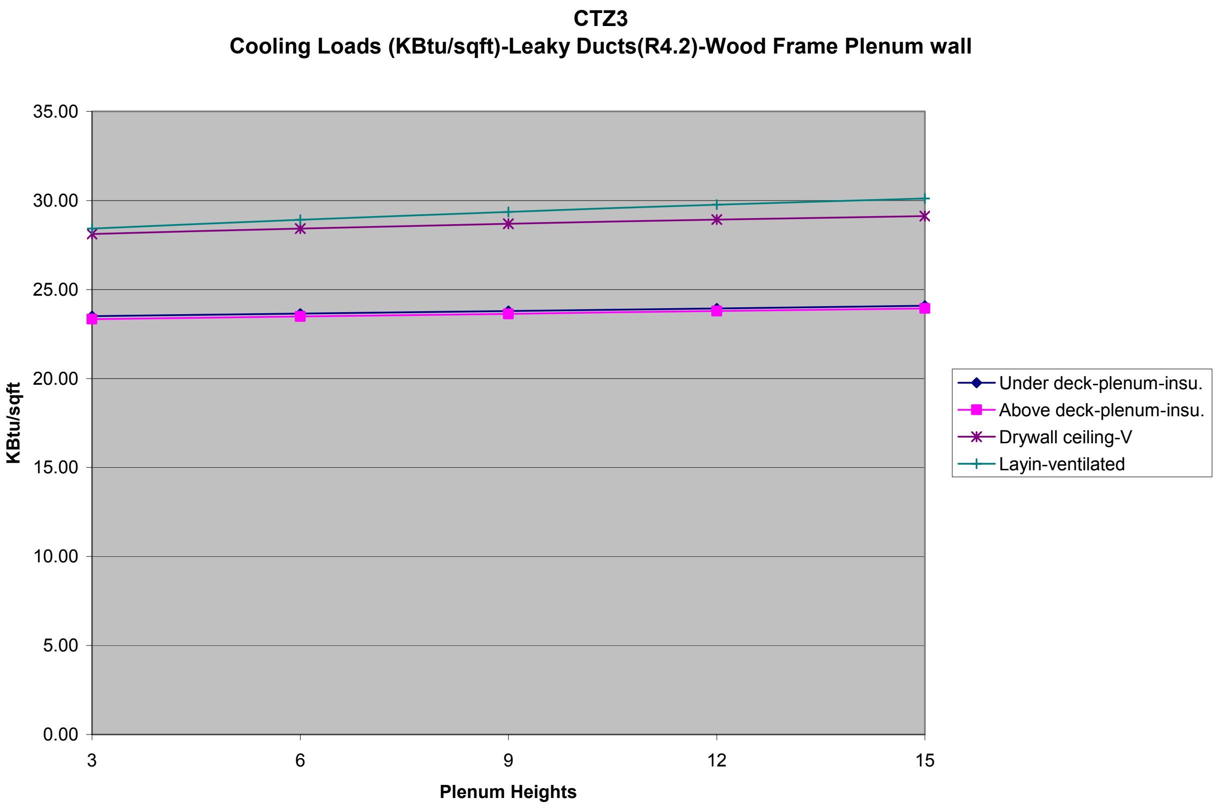

Figure 17 -- Cooling Loads, Leaky Ducts (R4.2) Wood Frame Plenum Wall

Effects of Insulation Location on Heating Loads

Climate Zone 3

The Lay-in ceiling was observed to have the maximum heating loads. A small increase in heating loads with increasing plenum heights was observed for all insulation conditions. The under deck and above deck roofs with insulated plenum and drywall ceiling showed minimum heating loads and almost overlap together in the values.

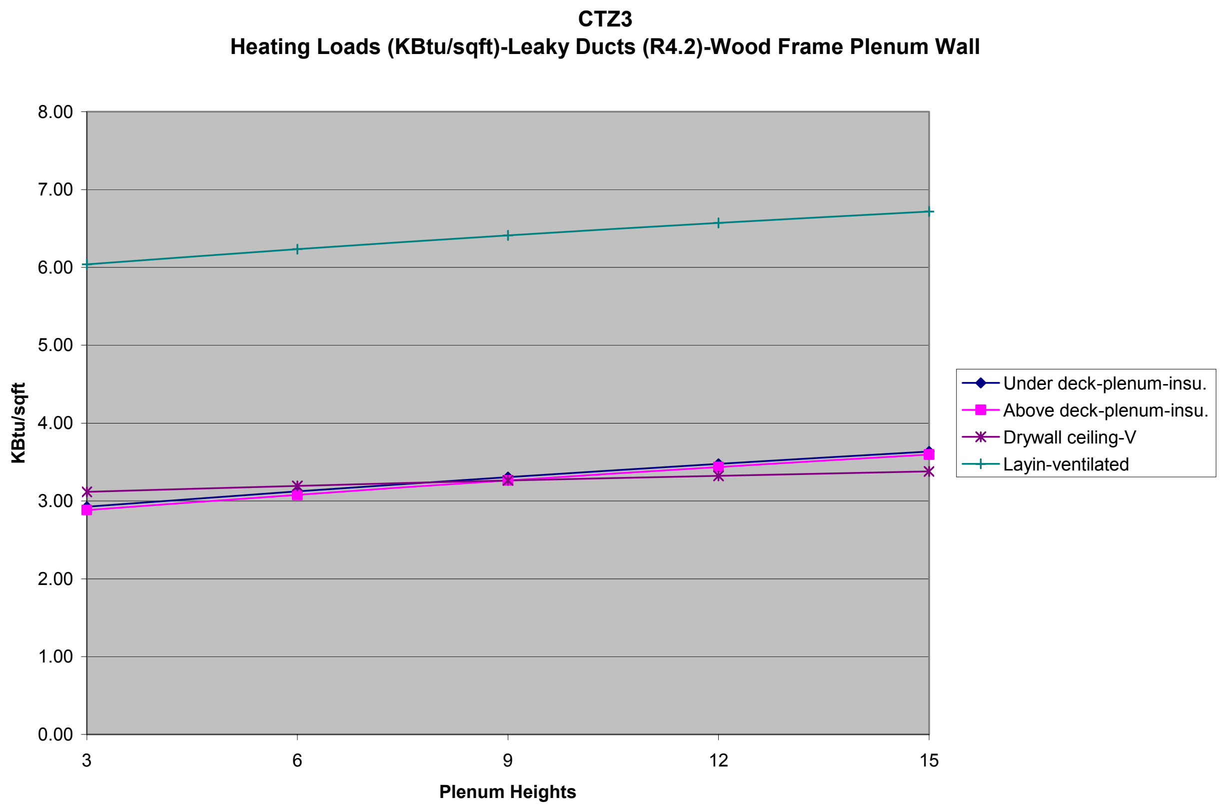

Figure 18 -- Heating Loads, Leaky Ducts (R4.2) Wood Frame Plenum Wall

Effects of Insulation Position on TDV Savings

Climate Zone 3

The roof decks with insulated plenum wall showed maximum TDV savings which could be attributed to them having low values for cooling and heating loads. There was slight increase on TDV savings with the increase in plenum heights for this case. The drywall showed the least amounts of savings and showed a slight increase with increasing plenum heights.

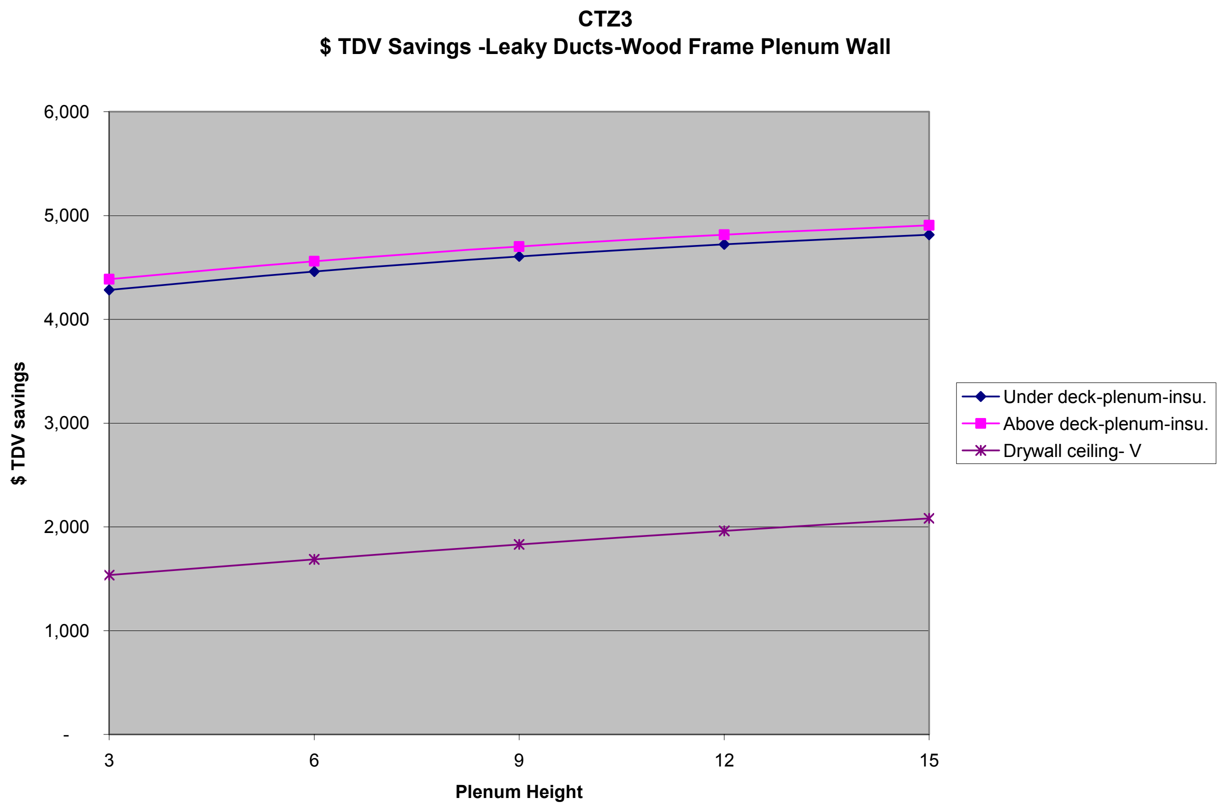

Figure 19 -- TDV Savings, Leaky Ducts Wood Frame Plenum Wall

Benefit Cost Ratio

Climate Zone 12

1. Benefit cost ratios of tightening and adding insulation to ducts for insulated roofs, drywall and lay-in ceilings from leaky (R 4.2) to tight (R 8) for plenum heights 3ft, 6ft, 9ft, 12ft and 15ft

Table 69 -- Benefit Cost Ratios of Tightening and Adding Insulation to Ducts for Insulated Roofs and Drywall and Lay-In Ceilings from Leaky (R 4.2) to Tight (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 12

CTZ12 Benefit cost ratio for Tightening Ducts for all insulation conditions				
	Insulated Plenum Wall		***Uninsulated Plenum Wall***	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling- V	Lay-in-V
3	**0.93**	**0.85**	7.61	5.24
6	1.04	**0.97**	8.26	5.92
9	1.15	1.07	8.86	6.58
12	1.27	1.20	9.39	7.20
15	1.40	1.32	9.86	7.76

2. Benefit cost ratios of insulated roof decks with leaky ducts (R 4.2) versus insulated lay-in ceilings with tight ducts (R 8)-Climate zone 3 for plenum heights of 3ft, 6ft, 9ft, 12ft and 15ft.

Table 70 -- Benefit Cost Ratio of Insulated Roofs With Leaky Ducts (R4.2) Versus Insulated Lay-In Ceiling With Tight Ducts (R 8) for Plenum Heights 3ft, 6ft, 9ft, 12ft and 15ft -Climate Zone 12

CTZ12 Benefit cost ratio for Leaky roofs vs tight layin ceilings		
	Insulated Plenum Wall	
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.
3	15.41	2.84
6	7.62	2.41
9	5.04	2.08
12	3.74	1.82
15	2.95	1.60

3. Benefit Cost Ratio for Insulated roof decks and drywall ceiling with tight ducts (R 8) versus insulated lay-in ceiling with tight ducts (R 8).

Table 71 -- Benefit Cost Ratio of Insulated Roofs and Drywall Ceilings With Tight Ducts (R 8) Versus Insulated Lay-In Ceilings With Tight Ducts (R 8) for Plenum Heights of 3ft, 6ft, 9ft, 12ft and 15ft- Climate Zone 12

CTZ12 Benefit cost ratio- Tight Ducts (R 8)			
Plenum Hts	Under deck-plenum-insu.	Above deck-plenum-insu.	Drywall ceiling-V
3	5.93	2.34	1.35
6	4.45	2.09	1.43
9	3.56	1.88	1.50
12	2.96	1.71	1.56
15	2.53	1.56	1.61

Appendix D -- Detailed Cost Estimates

	RS Means	Average from Surveys
Suspended Acoustic Ceiling		
Mineral Fiber on 15/16" T bar suspension 2' x 2' x 3/4" lay-in board	3.46 $/SF	2.06 $/SF
2' x 4' x 5/8" tile	2.34 $/SF	1.36 $/SF
Fiberglass ceiling board, 2' x 4' x 3/4", plane faced	3.19 $/SF	2.09 $/SF
Offices, 2' x 4' x 5/8"	2.21 $/SF	1.77 $/SF
Laid-in Insulation		
Fiberglass, Kraft faced batts or blankets 6" tk, R-19 23"wide	0.69 $/SF	0.46 $/SF
Foil faced R-19	0.74 $/SF	0.61 $/SF
Fiberglass, Kraft faced batts or blankets 3-1/2" tk, R-11 23"wide	0.52 $/SF	0.34 $/SF
Foil faced R-11	0.60 $/SF	0.50 $/SF
Below deck Insulation (Panalized 2x6 w/ 24 oc and 8' bay - stapled to wood)		
Fiberglass, Foil faced batts or blankets 6" tk, R-19 23"wide	0.74 $/SF	0.70 $/SF
Unfaced R-19	0.70 $/SF	0.55 $/SF
(Metal Deck using imapling pins)		
Fiberglass, Foil faced batts or blankets 6" tk, R19 23"wide		0.97 $/SF
Unfaced R-19		0.82 $/SF
Fiberglass, Foil faced batts or blankets 3-1/2" tk, R-11 23"wide		0.86 $/SF
Unfaced R-11		0.71 $/SF
Below deck Insulation (Concrete Slab - Ins attached with glue pins)		
Fiberglass, Foil faced batts or blankets 6" tk, R-19 23"wide		1.10 $/SF
Unfaced R-19		0.92 $/SF
Above deck insulation		
25 PSI comp strength, 4" tk, R-20	1.70 $/SF	1.70 $/SF
25 PSI, R-11	1.21 $/SF	1.06 $/SF
IB System 100 - 3600 SF Project		3.60 $/SF
Above 3600 SF		2.75 $/SF
Dry Wall ceiling		
Framing only using hanging t-bars - Sheetrock is screwed onto it	1.31 $/SF	2.17 $/SF
+ taping and finishing	3.13 $/SF	3.42 $/SF
Framing using studs spanning across walls. Max is 16ft. span		2.11 $/SF
+ taping and finishing		3.10 $/SF
Side Wall Insulation		
Side Wall Insulation for tilt up walls (Using stick pins or Impaling pins)		
Fiberglass, unfaced batts or blankets 3-1/2" tk, R-11 23"wide		0.58 $/SF
Foil faced R-11		0.77 $/SF
Unfaced R-13		0.66 $/SF
Foil faced R-13		0.84 $/SF
Side Wall Insulation for framed walls (insulation pushed in place)		
Fiberglass, unfaced batts or blankets 3-1/2" tk, R-11 23"wide	0.50 $/SF	0.30 $/SF
Foil faced R-11	0.60 $/SF	0.53 $/SF
Unfaced R-13	0.54 $/SF	0.40 $/SF
Foil faced R-13	0.62 $/SF	0.60 $/SF
Using furring, R-11 non rigid unfaced insulation	0.43 $/SF	0.70 $/SF
Using furring, R-13 non rigid unfaced insulation	0.43 $/SF	0.78 $/SF